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NUREG–2214

Managing Aging Processes In Storage (MAPS) Report

Draft Report for Comment

Office of Nuclear Materials Safety and Safeguards

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ABSTRACT

This Managing Aging Processes in Storage (MAPS) Report provides guidance for the U.S. Nuclear Regulatory Commission (NRC) technical reviewer. It establishes a technical basis for the safety review of renewal applications for specific licenses of independent spent fuel storage installations and Certificates of Compliance for dry storage systems, as codified in Title 10 of the *Code of Federal Regulations* Part 72, “Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste.”

The MAPS Report evaluates known aging degradation mechanisms to determine if they could affect the ability of dry storage system components to fulfill their safety functions in the 20- to 60-year period of extended operation. The guidance also provides examples of aging management programs that are considered generically acceptable to address the credible aging mechanisms to ensure that the design bases of dry storage systems will be maintained. An applicant for a renewed license or Certificate of Compliance may reference the information in the MAPS Report to support its aging management review and proposed aging management programs.

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ABBREVIATIONS AND ACRONYMS

ACI	American Concrete Institute
ADAMS	Agencywide Documents Access and Management System
AISC	American Institute of Steel Construction
AMP	aging management program
AMR	aging management review
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASR	alkali-silica reaction
B&PV	boiler and pressure vessel
BWR	boiling-water reactor
CAP	corrective action program
CFR	*Code of Federal Regulations*
CoC	Certificate of Compliance
CISCC	chloride-induced stress corrosion cracking
CWSR	cold worked stress relieved
DBTT	ductile-to-brittle transition temperature
DEF	delayed ettringite formation
DHC	delayed hydride cracking
DOE	U.S. Department of Energy
DSC	dry shielded canister
DSS	dry storage system
EPRI	Electric Power Research Institute
FSAR	final safety analysis report
HBU	high burnup
HDRP	HBU Dry Storage Cask Research and Development Project
HSM	horizontal storage module
IFBA	integral fuel burnable absorber
IN	Information Notice
ISFSI	independent spent fuel storage installation
ISG	Interim Staff Guidance
MAPS	Managing Aging Processes in Storage
MIC	microbiologically influenced corrosion
MPC	multipurpose canister
NDE	nondestructive examination
NRC	U.S. Nuclear Regulatory Commission
PCMI	pellet-to-cladding mechanical interaction
PWR	pressurized-water reactor
QA	quality assurance

RIA	reactivity-initiated accident
RXA	recrystallized annealed
SCC	stress corrosion cracking
SNF	spent nuclear fuel
SSC	structure, system, and component
TC	transfer cask
TLAA	time-limited aging analysis
TMI	Three Mile Island
TN	Transnuclear Inc.
TS	technical specification(s)
TSC	transportable storage canister
VCC	ventilated concrete cask
VVM	vertical ventilated module

Units of Measure

atm	atmosphere (pressure)
C	Celsius
dpa	displacements per atom (radiation damage)
F	Fahrenheit
g	gram
gal	gallon
GWd/MTU	gigawatt-days per metric ton of uranium
in	inch
K	Kelvin
kGy	kilogray (absorbed radiation dose)
ksi	1,000 pounds per square inch
L	liter
mg	milligram, 0.001 grams
MPa	megapascal, 1x10^{6} pascals (stress)
MeV	megaelectron-volt, 1x10^{6} electron-volts (energy)
mil	one-thousandth of an inch, 0.001 inch
mpy	mils per year
mm	millimeter, 0.001 meter
n	neutrons
oz	ounce
ppm	parts per million
psi	Pounds per square inch
rad	(unit of absorbed radiation dose)
sec	second
μm	micrometer, 1x10^{-6} meter
yr	year

1 INTRODUCTION

1.1 Purpose and use of the MAPS Report

The U.S. Nuclear Regulatory Commission (NRC) licenses the storage of spent nuclear fuel (SNF) in dry storage systems (DSSs) under the regulations of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste." To date, licenses for specific independent spent fuel storage installations (ISFSIs) or Certificates of Compliance (CoCs) for DSSs have been issued for initial terms of 20 years, although regulations currently allow an initial 40-year storage period. Licenses and CoCs can be renewed for additional terms not to exceed 40 years. In accordance with 10 CFR 72.42, "Duration of License; Renewal," and 10 CFR 72.240, "Conditions for Spent Fuel Storage Cask Renewal," renewal applications must include:

i. time-limited aging analyses (TLAAs) that demonstrate that structures, systems, and components (SSCs) important to safety will continue to perform their intended function for the requested period of extended operation

ii. aging management programs (AMPs) for management of issues associated with aging that could adversely affect SSCs important to safety

NUREG–1927, Revision 1, "Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel," provides guidance for the staff's review of TLAAs and AMPs (NRC, 2016).

This Managing Aging Processes in Storage (MAPS) Report is a technical basis document that provides additional guidance to NRC staff to improve the effectiveness and efficiency of the renewal process for the dry storage of SNF. The MAPS Report provides a generic evaluation of the aging mechanisms that have the potential to challenge the ability of DSS SSCs to fulfill their important-to-safety functions. The MAPS Report also describes acceptable generic AMPs that an applicant may use to maintain the approved design basis of its storage system during the period of extended operation (from 20 to 60 years of storage[1]). An applicant for a renewed license or CoC may reference the information in the MAPS Report to support its design-specific aging management review (AMR) and proposed AMPs.

The content of the report is as follows.

- Chapter 1 briefly describes how the MAPS Report is to be used by the NRC staff.

- Chapter 2 defines the terms that are used throughout this report, including descriptions of materials, environments, aging mechanisms, and aging effects (the manifestations of aging mechanisms by degraded conditions or performance).

- Chapter 3 evaluates the aging mechanisms that may challenge the ability of SSCs to fulfill their important-to-safety function(s). Those mechanisms that are shown to have the potential to adversely affect an important-to-safety function in the 60-year timeframe

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[1] Because the NRC has granted, to date, initial storage licenses and CoCs for 20 years only, the MAPS Report considers the effects of aging for 40 years beyond the initial 20-year term (or 60 years total).

are identified as “credible.” This chapter provides the technical bases for the aging management recommendations that appear in the AMR tables and AMPs in Chapters 4 and 5, respectively.

- Chapter 4 describes selected DSS designs and provides AMR tables for those designs. The AMR tables identify the aging mechanisms and effects that could challenge the capability of each SSC to fulfill its important-to-safety function(s) in the 20- to 60-year period of extended operation. For those credible aging effects, the AMR tables recommend aging management approaches (i.e., AMPs, TLAAs, or other analyses).

- Chapter 5 provides guidance for identifying and evaluating time-limited aging analyses

- Chapter 6 contains example AMPs that an applicant may use to address the credible aging effects identified in the AMR tables.

Figure 1-1 provides a flowchart that shows how the guidance in the MAPS Report supports the renewal process.

The MAPS Report increases the efficiency of the licensing process by reducing redundant reviews of the same topic. If an applicant credits the information in the MAPS Report in the renewal application, the staff should ensure that the applicant demonstrates that the design features, environmental conditions, and operating experience for the subject ISFSI or DSS are bounded by those evaluated in the MAPS Report. Otherwise, the staff should ensure that the applicant revises its AMR and AMPs, as appropriate, to address the design or operating parameters applicable to its facility or storage system.

The MAPS Report contains one acceptable method to identify and manage credible aging mechanisms and effects for specific-license and CoC renewals. An applicant may propose alternatives for staff review. As such, the staff should not use the MAPS Report as a requirement. Nevertheless, its use should facilitate both the preparation of a specific license or CoC renewal application by an applicant and a timely, consistent review by the NRC staff.

Finally, the MAPS Report does not address the scoping of SSCs for specific-license or CoC renewal; this is addressed in Chapter 2 of NUREG–1927, Revision 1. Although the MAPS Report generically addresses SSCs for several storage system designs, scoping is design and license specific. The inclusion of a certain SSC in the MAPS Report does not necessarily imply that the particular SSC is within the scope of renewal for all ISFSIs or DSSs. Conversely, the omission of a certain SSC in the MAPS Report does not imply that the particular SSC is not within the scope of renewal for any ISFSI or DSS.

1.2 Scope of report

The MAPS Report addresses the aging mechanisms and effects associated with the following DSS designs: Standardized and Advanced NUHOMS, HI-STORM 100, HI-STAR 100, TN-32 and -68, the NAC UMS, MPC, and MAGNASTOR systems, and the FuelSolutions storage system. The selection of these systems addresses near-term renewal applications and a variety of storage system designs. Although this report was written to specifically address those designs, the staff may consider the general applicability of this guidance to other designs.

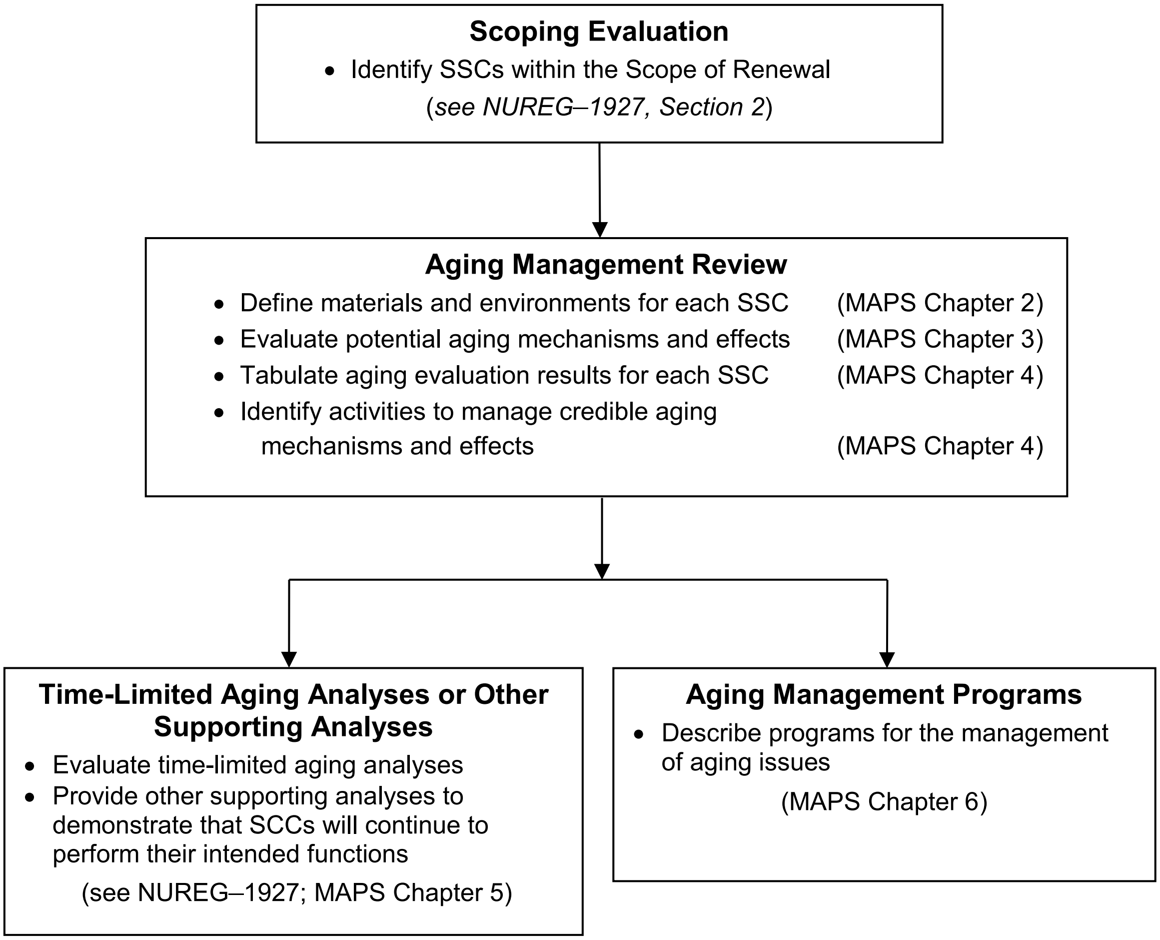

Figure 1-1 Use of the MAPS Report in the renewal process

1.3 Acknowledgments

The NRC would like to acknowledge the contributions of the staff at the Center for Nuclear Waste Regulatory Analyses at the Southwest Research Institute® for its role in developing the technical bases for the aging evaluations in this report. This includes the evaluations of the aging mechanisms in Chapter 3 and the associated AMR tables in Chapter 4. The staff at the CNWRA also assisted in the development of the introductory material and combining all portions of this document into a single, cohesive report.

The NRC also would like to acknowledge the contributions of Argonne National Laboratory in support of the U.S. Department of Energy (DOE) Used Fuel Disposition Campaign. Portions of the storage system descriptions in Chapter 4 of the MAPS Report were taken from the information contained in Chapter V of the Argonne/DOE report, “Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel” (Chopra et al., 2014).

1.4 References

Chopra, O., D. Diercks, R. Fabian, Z. Han, and Y. Liu. "Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel." FCRD–UFD–2014–000476. ANL–13/15, Rev. 2. Washington, DC.: U.S. Department of Energy. 2014.

NRC. NUREG–1927, "Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel." Revision 1. Washington, DC.: U.S. Nuclear Regulatory Commission. Agencywide Documents Access and Management System Accession No. ML16179A148. 2016.

2 DEFINITIONS

This chapter defines the usage of terms in the technical basis discussions in Chapter 3, the aging management review (AMR) tables in Chapter 4, and the aging management programs in Chapter 5. Selected definitions and usage are provided for the materials of construction, service environments, aging mechanisms, and aging effects (the manifestations of aging mechanisms by degraded conditions or performance).

2.1 Materials

Table 2-1 describes many of the terms used to describe the materials of construction for the dry storage systems (DSSs).

Table 2-1 Use of terms for materials

Term	Usage in This Document
Aluminum	Includes commercially pure aluminum 1100 and precipitation-hardened alloys 6061 and 6063.
BISCO NS-3	A castable cementitious material for neutron and gamma shielding applications that may be blended with boron fillers to enhance neutron attenuation. It is fully encased in a metal, such as aluminum or steel.
Boral®	A laminate composite that is used as a neutron poison material. It consists of a core of aluminum and boron-carbide powder sandwiched between sheets of aluminum. The boron-carbide content in the core ranges from 35 to 65 weight percent.
Boralyn®, Metamic™	Two variations of boron-carbide aluminum metal-matrix composite for neutron poison applications, one with billets produced by vacuum hot pressing (Boralyn®) and the second produced by cold isostatic pressing followed by vacuum sintering (Metamic™).
Borated aluminum	An aluminum alloy typically containing up to 4.5 weight percent boron. It is used as a neutron poison material. The boron is incorporated in the aluminum matrix as discrete particles of AlB_2 or TiB_2 (for alloys also containing titanium). Aluminum alloys 1100, 6063, and 6351 have been used as base materials for boron additions.
Borated polymers	Borated polymers include borated polyester resin and polypropylene for neutron shielding applications. Borated polyester resin is an unsaturated polyester crosslinked with styrene and typically contains about 50 weight percent mineral and fiberglass reinforcement.
Borated stainless steel	An austenitic chromium-nickel steel with boron additions up to 2.5 weight percent. It is used as a neutron poison material. The boron in the form of borides is dispersed in the Type 304 stainless steel matrix as an intermetallic phase.
Concrete	A mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials.

Table 2-1 Use of terms for materials	
Term	**Usage in This Document**
Copper alloys	Copper alloys used in DSSs include bronzes (copper alloyed with tin) and brasses (copper alloyed with zinc).
Holtite-A™	A Holtec neutron shielding material consisting of epoxy polymer, B_4C added as a finely divided powder, and aluminum hydroxide. It is fully encased in a metal enclosure.
Nickel alloys	Nickel alloys include Inconel 718 and X750. Inconel is a family of austenitic nickel-chromium-based superalloys. Both Inconel 718 and X750 are precipitation-hardening alloys.
Stainless steel	Stainless steel includes Types 304, 316, XM-19, SA193-Gr. B8, SA351-Gr. CF3, and Nitronic 60 austenitic stainless steels and Type 630 precipitation-hardening martensitic stainless steel. Type 630 stainless steel is commonly referred to as 17-4PH and contains 15–17.5 percent chromium, 3–5 percent copper, and 3–5 percent nickel (in weight percent). Chrome-plated stainless steel is also included in the category of stainless steel.
Steel	Various carbon steels, alloy steels, and high-strength, low-alloy steels. Examples of steel designations included in this category are ASTM A36, ASTM A320-Gr. L43, ASTM F436, SA36, SA193-Gr. B7, SA203-Gr. D/E, SA266-Cl. 2, SA320-Gr. L43, SA350-Gr. LF2/LF3, SA414, SA508-Cl. 1A/3A, SA516-Gr. 70, SA533-Gr. B, SA537-Cl. 2, SA540-Gr. B23/24, SA620, and SA696-Gr. B. Galvanized steel, aluminum-coated steel, and electroless nickel-plated steel are also included in the category of steel.
Zirconium-based alloys	The materials of construction of fuel cladding and fuel assembly hardware. Various zirconium-based materials have been used in commercial reactor applications because of their low neutron cross section and excellent corrosion resistance to a variety of environmental conditions. The cladding types Zircaloy-2, Zircaloy-4, ZIRLO™, and M5® are included in this category. Zirconium-based cladding in high burnup (HBU) spent nuclear fuel refers to assembly-average burnups exceeding 45 GWd/MTU.

2.2 Environments

Table 2-2 defines many of the environments to which DSS SSCs are exposed.

Table 2-2 Use of terms for environments

Term	Usage in This Document
Air–outdoor (OD)	Direct exposure to weather, including precipitation and wind; possibly salt laden. The indoor air environment to which transfer cask components are typically exposed is conservatively evaluated as outdoor air.
Demineralized water (DW)	Water that has been treated to remove dissolved minerals. Demineralized water is used as the liquid neutron shield in transfer casks.
Embedded in: Concrete (E-C) Metal (E-M) Neutron shielding (E-NS)	When one or more surfaces of a component are in contact with another component or material. This may prevent ingress of water and contaminants to the embedded surface, depending on the permeability of the embedding environment.
Fully encased or lined (FE)	The environment of some concrete structures that are fully enclosed inside another component or fully lined by another material (e.g., steel), which prevents ingress of water and contaminants. Also, ceramic fiber insulation is fully encased in foil-facing or jacketing.
Helium (HE)	The helium fill gas inside a canister or cask and trace quantities of other gases, such as nitrogen, oxygen, argon, and fission product gases. This environment applies to fuel, cladding, and other internal components inside a cask.
Groundwater/soil (GW)	Groundwater is subsurface water found in wells, tunnels, or drainage galleries, or water that flows naturally to the earth's surface via seeps or springs. Soil is a mixture of organic and inorganic materials produced by the weathering of rock and clay minerals or the decomposition of vegetation. Voids containing air and moisture can occupy 30 to 60 percent of the soil volume. Below-grade concrete structures are assumed to be partially exposed to a groundwater or soil environment.
Sheltered (SH)	The environment outside a sealed canister but within the confined internal space of a shielding structure (e.g., overpack or horizontal storage module). The sheltered environment is open to outdoor air, but it is shielded from direct exposure to precipitation. This environment may contain moisture, salts, and other contaminants from the outdoor air.

2.3 Aging mechanisms

Table 2-3 defines the aging mechanisms that are evaluated in this report.

Table 2-3 Use of terms for aging mechanisms

Term	Usage in This Document
Aggressive chemical attack	The degradation of concrete by strong acids. Chlorides and sulfates of potassium, sodium, and magnesium may attack concrete, depending on their concentrations in the soil/groundwater that comes into contact with the concrete. The minimum thresholds causing concrete degradation are 500 ppm chloride and 1,500 ppm sulfate.
Boron depletion	The degradation of the neutron-absorbing capacity of neutron poison and shielding materials when they are exposed to neutron fluence.
Corrosion	The electrochemical reaction of a metal or metal alloy in an environment that results in oxidation or wastage of the material.
Creep	Creep, for a metallic material, refers to a time-dependent continuous deformation process under constant stress. It is a thermally activated process and is generally a concern at temperatures greater than 40 percent of the material's absolute melting temperature. However, low-temperature creep is an athermal process that is considered as a potential degradation mechanism for some alloys, including zirconium-based alloys. In concrete, creep is related to the loss of absorbed water from the hydrated cement paste. It is a function of the modulus of elasticity of the aggregate.
Crevice corrosion	Localized corrosion in joints, connections, and other small, close-fitting regions that develop local aggressive environments.
Dehydration at high temperatures	Dehydration reactions of the hydrated cement paste in concrete when exposed to temperatures greater than 65 degrees C [149 degrees F]. Dehydration can degrade concrete strength and increase susceptibility to cracking. The degree of concrete degradation depends on several factors, including concrete mixing, aggregate type, curing, loading condition, moisture retention and content, and exposure time.
Delayed ettringite formation	During concrete curing, the naturally occurring ettringite (a calcium aluminum sulfate mineral) converts to monosulfoaluminate if curing temperatures are greater than about 70 degrees C [158 degrees F]. After concrete hardens, ettringite will reform if the temperature decreases below about 70 degrees C [158 degrees F], resulting in concrete cracking and spalling. The conditions necessary for the occurrence of delayed ettringite formation are excessive temperatures during concrete casting, the presence of internal sulfates, and a moist environment.

Table 2-3 Use of terms for aging mechanisms

Term	Usage in This Document
Delayed hydride cracking	The propagation of a crack in zirconium-based cladding materials as a result of diffusion of hydrogen to a crack tip and the embrittlement of the near-tip region due to hydride precipitation. The operability of the delayed-hydride-cracking mechanism in fuel cladding depends on the stress imposed on the cladding.
Erosion	Soil erosion, or removal, is primarily caused by rainfall and surface runoff, floods, or wind. Soil erosion can affect the stability of concrete structures, resulting in scouring that is a localized loss of soil, often around a foundation element. Factors that affect the erosion rates include soil structure and composition, climate, topography, and vegetation cover.
Fatigue	Also termed "cyclic loading" or "thermal/mechanical fatigue." Fatigue is a phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material. Fatigue fractures are progressive and grow under the action of the fluctuating stress. Fatigue due to cyclic thermal loads is defined as the structural degradation that can occur from repeated stress/strain cycles caused by fluctuating loads and temperatures. After repeated cyclic loading of sufficient magnitude, microstructural damage may accumulate, leading to macroscopic crack initiation at the most vulnerable regions. Subsequent mechanical or thermal cyclic loading may lead to growth of the initiated crack.
Freeze-thaw	Repeated freezing and thawing of water can cause degradation of concrete, characterized by scaling, cracking, and spalling. The cause is water freezing within the pores of the concrete, creating hydraulic pressure.
Galvanic corrosion	Accelerated corrosion of a metal when in electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.
General corrosion	Uniform loss of material due to corrosion, proceeding at approximately the same rate over a metal surface.
Hydride reorientation and hydride-induced embrittlement	The precipitation of radial hydrides results in embrittlement of zirconium-based cladding materials under pinch-load stresses at low-to-moderate temperatures. Reorientation of hydrides from the circumferential-axial to radial-axial direction is caused by heating and cooling of the cladding under sufficient cladding hoop tensile stresses.

Table 2-3 Use of terms for aging mechanisms

Term	Usage in This Document
Leaching of calcium hydroxide	The dissolution of calcium-containing concrete components (e.g., calcium hydroxide) when water passes through either cracks, inadequately prepared construction joints, or areas not sufficiently consolidated during placing. Once the calcium hydroxide has been leached away, other cementitious constituents become vulnerable to chemical decomposition, finally leaving only the silica and alumina gels behind and lowering the strength of the concrete. The water's aggressiveness in the leaching of calcium hydroxide depends on its salt content, pH, and temperature. This leaching action is effective only if the water flows through the concrete.
Mechanical overload	The overload of fuel cladding due to fuel pellet swelling. Fuel pellet swelling is the result of decay gas production in the pellet. Pellet swelling can increase stresses on the cladding.
Microbiological degradation	Biodegradation attack of concrete by organisms growing on its surfaces under favorable environmental conditions (e.g., moisture, near neutral pH, presence of nutrients), causing an increase in concrete porosity and permeability and the loss of material by spalling or scaling.
Microbiologically influenced corrosion	Any of the various forms of corrosion influenced by the activity of such microorganisms as bacteria, fungi, and algae, and/or the products of their metabolism. For example, anaerobic bacteria can establish an electrochemical galvanic reaction or disrupt a passive protective film; acid-producing bacteria can produce corrosive metabolites.
Oxidation	A corrosion reaction. In this report, oxidation also is a defined aging mechanism describing the reaction of zirconium alloy fuel rod cladding with water to form zirconium oxide..
Pitting corrosion	A localized form of corrosion that is confined to a point or small area of a metal surface. It takes the form of cavities called pits.
Radiation damage and radiation embrittlement	The loss of ductility, fracture toughness, and resistance to cracking of metals that may occur under exposure to neutron radiation. In concrete, radiation exposure can cause dissociation of water into hydrogen and oxygen, leading to decreased compressive and tensile strengths. The extent of radiation damage to concrete depends on the neutron and gamma fluence.
Reaction with aggregates	The presence of reactive alkalis in concrete can lead to subsequent reactions with aggregates that may lead to cracking, a loss of material, or an increase in porosity and permeability. These alkalis are introduced mainly by cement but also may come from admixtures, salt contamination, seawater penetration, or solutions of deicing salts. These reactions include alkali-silica reactions, cement-aggregate reactions, and aggregate-carbonate reactions.

Table 2-3 Use of terms for aging mechanisms

Term	Usage in This Document
Salt scaling	Salt scaling damage manifests as flaking of material from the concrete surface. Salt scaling takes place when concrete is exposed to freezing temperatures, moisture, and dissolved salts (e.g., deicing salts). This degradation mode affects mainly horizontal concrete surfaces where water ponding can be expected.
Settlement	Settlement of a concrete structure may occur due to changes in the site conditions (e.g., water table). The amount of settlement depends on the foundation material. In soil, loss of form due to settlement can occur during the first several years of placement. Factors that control soil settlement include the type of soil particles and particle packing, the amount of water used during the compaction process, and the height of soil fill.
Shrinkage	Shrinkage of concrete can result from cement hydration and loss of moisture during drying. Cracking and shortening of concrete due to shrinkage can occur early after concrete placement.
Stress corrosion cracking (SCC)	The cracking of a metal produced by the combined action of corrosion and a tensile stress (applied or residual). SCC is highly chemical specific in that certain alloys are likely to undergo SCC only when exposed to a small number of chemical environments.
Stress relaxation	A loss of preload in a heavily loaded bolt. Over time, the clamping force provided by a bolt may decrease due to atomic movement within the stressed bolt material (analogous to the metallic creep mechanism at elevated temperatures).
Thermal aging	Also termed “thermal aging embrittlement” or “thermal embrittlement.” Many materials are intentionally thermally aged during their manufacture to achieve desired mechanical properties. Continued exposure to elevated temperatures during operation can, in some cases, result in undesirable properties. For example, at operating temperatures of 300 to 400 degrees C [572 to 752 degrees F], austenitic stainless steel welds that contain ferrite exhibit a spinodal decomposition of the ferrite phase into ferrite-rich and chromium-rich phases. This may give rise to embrittlement (reduction in fracture toughness), depending on the amount, morphology, and distribution of the ferrite phase and the composition of the stainless steel.
Wear	The removal of surface material due to relative motion between two surfaces or under the influence of hard, abrasive particles. Wear occurs in parts that experience intermittent relative motion or frequent manipulation.

Table 2-3 Use of terms for aging mechanisms

Term	Usage in This Document
Wet corrosion and blistering	A degradation mechanism for neutron poison plates with open porosity as a result of water entering pores in the material during loading, leading to internal corrosion. Blisters occur from trapped hydrogen produced from corrosion reactions. Wet corrosion and blistering can cause dimensional changes affecting criticality considerations due to moderator displacement and may also hinder the retrieval of fuel assemblies.

2.4 Aging effects

An aging effect is the manifestation of an aging mechanism, as evidenced by a degraded condition or performance. Table 2-4 defines the aging effects described in this report.

Table 2-4 Use of terms for aging effects

Term	Usage in This Document
Changes in dimension	A change in the size of a component resulting from creep of aluminum and zirconium-based alloys. Changes in dimension also can be caused by wet corrosion and blistering of Boral® neutron poison materials.
Cracking	Crack initiation and growth in metallic components as a result of SCC, fatigue, and delayed hydride cracking. Cracking in concrete is a complete or incomplete separation of concrete into two or more parts produced by breaking or fracturing.
Increase in porosity and permeability	An increase in the percentage of the volume of voids in a concrete material or an increase in the susceptibility of concrete to permit liquids or gasses to pass through.
Loss of bond	A loss of the interacting force that prevents slip of the reinforcing steel bars relative to the surrounding concrete in a reinforced concrete member.
Loss of criticality control	A diminishment of the capability of neutron poison materials to maintain the subcriticality of spent nuclear fuel.
Loss of form	A change in the shape or position of soil resulting from settlement due to poor soil consolidation. In addition, soil tends to absorb moisture with time and thus promotes loss of form.
Loss of fracture toughness and loss of ductility	A decrease in the ability of a material to resist fracture. This phenomenon results from thermal aging embrittlement, radiation embrittlement, or hydrogen embrittlement.
Loss of material	The destructive removal of material due to general corrosion, pitting corrosion, crevice corrosion, galvanic corrosion, microbiologically influenced corrosion, or aggressive chemical attack. In concrete structures, loss of material can result from local flaking, spalling, or peeling away of the near-surface portion of hardened concrete.
Loss of preload	A reduction in the clamping force in a mechanically loaded joint.
Loss of shielding	A diminishment of the capability of a material to shield radiation.
Loss of strength	A decrease in the ability of a material to support a mechanical load. In metals, loss of strength may be due to thermal aging or annealing. In concrete structures, loss of strength can also be caused by the leaching of calcium hydroxide or reaction with aggregates.
None	A term used in the AMR tables for certain material and environment combinations that may not be subject to credible aging mechanisms; thus, there are no relevant aging effects that require management.

Table 2-4 Use of terms for aging effects

Term	Usage in This Document
Precursor to SCC	A material condition that initiates SCC. Both pitting and crevice corrosion are known to be precursors to SCC and, as such, can lead to cracking of stainless steel canisters.
Reduction of concrete pH (reducing corrosion resistance of steel embedments)	A decrease in the alkalinity of concrete. If the pH of concrete in which steel is embedded is reduced below 11.5 by intrusion of aggressive ions (e.g., chlorides > 500 ppm) in the presence of oxygen, embedded steel may corrode. A reduction in pH can be caused by carbonation.

3 EVALUATION OF AGING MECHANISMS

3.1 Introduction

This chapter evaluates known aging degradation mechanisms to determine which of those could adversely affect an important-to-safety function in the 20- to 60-year period of extended operation. These evaluations provide the technical bases for the recommendations in the aging management review (AMR) tables and aging management programs (AMPs) in Chapters 4 and 6, respectively. This chapter is first divided into major component areas (e.g., casks and internals, concrete overpacks), which in turn are subdivided into discussions of the aging mechanisms for each of the materials of construction (e.g., steel, aluminum).

Each evaluation in this chapter concludes with a determination of whether the aging mechanism is considered “credible” in the period of extended operation. A credible aging mechanism is one that could affect an important-to-safety function if the mechanism were not addressed by an aging management activity. The AMR tables in Chapter 4 recommend an AMP, time-limited aging analysis (TLAA), or other analysis to address the effects of aging.

Table 3-2 through Table 3-6 summarize the conclusions in this chapter. For each material, the tables show in which environments the aging mechanisms were determined to be credible and noncredible. Not all combinations of materials, environments, and aging mechanisms were evaluated in each major component area. This occurs because some material-environment combinations do not exist in every major component area or, in some instances, aging mechanisms were not considered to be reasonably plausible, and thus an evaluation was not performed. The reviewer should note that these conclusions are based only on a review of the specific storage system designs described in Section 1.2 and Chapter 4, and thus the reviewer should consider the credibility of aging mechanisms for other systems on a case-by-case basis.

Table 3-1 provides the environment abbreviations used in the summary tables.

Table 3-1 Environment abbreviations	
Outdoor air	OD
Demineralized water	DW
Embedded in concrete	E-C
Embedded in metal	E-M
Embedded in neutron shielding	E-NS
Fully encased or lined	FE
Helium	HE
Groundwater/soil	GW
Sheltered	SH

Table 3-2 Casks and internals aging mechanism evaluations

Material	Aging Mechanism	Credible Environments	Noncredible Environments	Section
Steel	General corrosion	OD, SH, DW, GW, E-C	E-M, E-NS, HE	3.2.1.1
	Pitting and crevice corrosion	OD, SH, DW, GW, E-C	E-M, E-NS, HE	3.2.1.2
	Galvanic corrosion*	OD, SH		3.2.1.3
	Microbiologically influenced corrosion (MIC)	GW, E-C	OD, SH, DW, E-M, E-NS, HE	3.2.1.4
	Stress corrosion cracking (SCC)		OD, SH	3.2.1.5
	Creep		OD, SH, DW, GW, E-M, E-NS, HE	3.2.1.6
	Fatigue	Evaluate design code TLAA, if applicable		3.2.1.7
	Thermal aging		OD, SH, DW, GW, E-M, E-NS, HE	3.2.1.8
	Radiation embrittlement		OD, SH, DW, GW, E-M, E-NS, HE	3.2.1.9
	Stress relaxation	SH	OD	3.2.1.10
	Wear	OD		3.2.1.11
Stainless Steel	General corrosion		OD, SH, DW, E-M, E-NS, HE	3.2.2.1
	Pitting and crevice corrosion[†]	OD, SH	DW, E-M, E-NS, HE	3.2.2.2
	Galvanic corrosion*	OD, SH		3.2.2.3
	MIC		OD, SH, DW, E-M, E-NS, HE	3.2.2.4
	SCC[‡]	OD, SH	DW, E-M, E-NS, HE	3.2.2.5
	Creep		OD, SH, DW, E-M, E-NS, HE	3.2.2.6
	Fatigue	Evaluate design code TLAA, if applicable		3.2.2.7
	Thermal aging	HE[§]	OD, SH, DW, E-M, E-NS	3.2.2.8
	Radiation embrittlement		OD, SH, DW, E-M, E-NS, HE	3.2.2.9
	Stress relaxation		OD, SH	3.2.2.10
	Wear	OD		3.2.2.11

*where dissimilar material galvanic couples exist

[†] as a precursor to SCC

[‡] SCC is credible at welds and other regions where sufficient stress exists; transfer cask components exposed to indoor/outdoor air are not considered to be susceptible to SCC because their surfaces are periodically rinsed with demineralized water.

[§] thermal aging is credible only for precipitation-hardened martensitic stainless steels

Table 3-2 Casks and internals aging mechanism evaluations (continued)

Material	Aging Mechanism	Credible Environments	Noncredible Environments	Section
Aluminum Alloys	General corrosion*	SH	E-M, E-NS, HE	3.2.3.1
	Pitting and crevice corrosion	SH	E-M, E-NS, HE	3.2.3.2
	Galvanic corrosion†	SH	HE	3.2.3.3
	MIC		SH, E-M, E-NS, HE	3.2.3.4
	Creep	analyses required‡		3.2.3.5
	Fatigue	Evaluate design code TLAA, if applicable		3.2.3.6
	Thermal aging	analyses required‡		3.2.3.7
	Radiation embrittlement		SH, E-M, E-NS, HE	3.2.3.8
Nickel Alloys	General corrosion		OD	3.2.4.1
	Pitting and crevice corrosion		OD	3.2.4.2
	MIC		OD	3.2.4.3
	SCC		OD	3.2.4.4
	Fatigue	Evaluate design code TLAA, if applicable		3.2.4.5
	Radiation embrittlement		OD	3.2.4.6
	Stress relaxation		OD	3.2.4.7
	Wear	OD		3.2.4.8
Copper Alloys	General corrosion	OD		3.2.5.1
	Pitting and crevice corrosion		OD	3.2.5.2
	MIC		OD	3.2.5.3
	Radiation embrittlement		OD	3.2.5.4
Lead	All		E-M	3.2.6
Depleted Uranium	All		E-M	3.2.7
Coatings	Radiation embrittlement	analyses required		3.2.8

*general corrosion is not considered to be credible for anodized aluminum

†where dissimilar metal couples exist

‡creep and thermal aging are relevant only for load-bearing components.

Table 3-3 Neutron shielding materials aging mechanism evaluations

Material	Aging Mechanism	Credible Environments	Noncredible Environments	Section
Neutron Shielding	Boron depletion	analyses required		3.3.1.1
	Thermal aging	FE*		3.3.1.2
	Radiation embrittlement	FE*		3.3.1.3

*thermal aging and radiation embrittlement are credible only for polymer-based neutron-shielding materials.

Table 3-4 Neutron poison materials aging mechanism evaluations

Material	Aging Mechanism	Credible Environments	Noncredible Environments	Section
Borated Stainless Steels	General corrosion		HE	3.4.1
	Galvanic corrosion		HE	3.4.1
	Wet corrosion and blistering		HE	3.4.1
	Boron depletion		HE*	3.4.1.1
	Creep		HE	3.4.1.2
	Thermal aging		HE	3.4.1.3
	Radiation embrittlement		HE	3.4.1.4
Borated Aluminum and Aluminum-based Composites	General corrosion		HE	3.4.2.1
	Galvanic corrosion		HE	3.4.2.2
	Wet corrosion and blistering		HE	3.4.2.3
	Boron depletion		HE*	3.4.2.4
	Creep		HE†	3.4.2.5
	Thermal aging		HE†	3.4.2.6
	Radiation embrittlement		HE	3.4.2.7

*when a boron depletion analysis is included in the design basis, applicants must provide a TLAA to demonstrate that depletion will not challenge noncriticality in the period of extended operation

†creep and thermal aging are relevant only for load-bearing aluminum components.

Table 3-5 Concrete overpacks, support pads, and ceramic fiber insulation aging mechanism evaluations

Material	Aging Mechanism	Credible Environments	Noncredible Environments	Section
Concrete	Freeze and thaw	OD, GW (above freeze line)	SH, FE, GW (below freeze line)	3.5.1.1
	Creep		all	3.5.1.2
	Reaction with aggregates	all*		3.5.1.3
	Differential settlement	OD, SH, GW		3.5.1.4
	Aggressive chemical attack	OD, GW	SH, FE	3.5.1.5
	Corrosion of reinforcing steel	OD, GW	SH, FE	3.5.1.6
	Shrinkage		OD, SH, GW, FE	3.5.1.7
	Leaching of calcium hydroxide	OD, SH, GW	FE	3.5.1.8
	Radiation damage		OD, SH, GW, FE	3.5.1.9
	Fatigue		OD, SH, GW, FE	3.5.1.10
	Dehydration at high temperature		OD, SH, GW, FE	3.5.1.11
	Microbiological degradation	GW	OD, SH, FE	3.5.1.12
	Delayed ettringite formation		OD, SH, GW, FE	3.5.1.13
	Salt scaling	OD, GW (above freeze line)	SH, FE, GW (below freeze line)	3.5.1.14
Ceramic Fiber Insulation	Radiation damage	analysis required		3.5.2.1
	Moisture absorption		3.5.2.2	3.5.2.2

*where moisture is available

Table 3-6 Spent fuel assembly aging mechanism evaluations

Material	Aging Mechanism	Credible Environments	Noncredible Environments	Section
Cladding Materials (Zirconium-based Alloys)	Hydride reorientation†	HE*		3.6.1.1
	Delayed hydride cracking†		HE	3.6.1.2
	Thermal creep†	HE		3.6.1.3
	Low-temperature creep†		HE	3.6.1.4
	Mechanical overload†		HE	3.6.1.5
	Oxidation		HE	3.6.1.6
	Pitting corrosion		HE	3.6.1.7
	Galvanic corrosion		HE	3.6.1.8
	SCC		HE	3.6.1.9
	Radiation embrittlement		HE	3.6.1.10
	Fatigue		HE	3.6.1.11
Assembly Hardware Materials (Zirconium-based, Inconel, and Stainless Steel Alloys)	Creep		HE	3.6.2.1
	Hydriding		HE	3.6.2.2
	General corrosion		HE	3.6.2.3
	SCC		HE	3.6.2.4
	Radiation embrittlement		HE	3.6.2.5
	Fatigue		HE	3.6.2.6

*Although hydride reorientation and hydride-induced embrittlement of high-burnup cladding is credible, these mechanisms are only expected to potentially compromise intended functions under pinch-type loads. Such loads are not expected to be present during storage.

†applicable to high-burnup fuel

3.2 Casks and internals

"Casks and internals" include various metallic subcomponents of the storage casks or canisters, the fuel baskets and other internal subcomponents (other than spent fuel assemblies), the storage modules or overpacks, and the transfer casks. These subcomponents are exposed to several environments within and outside the dry storage systems (DSSs), such as sheltered environments, indoor air, outdoor air, demineralized water, groundwater or soil, helium, and embedded environments. The spent nuclear fuel (SNF) also exposes subcomponents to elevated temperatures and radiation, with heat exposure and dose depending on the subcomponent location and the SNF characteristics (e.g., burnup and age of spent fuel). The materials of construction for these subcomponents include steel, stainless steel, aluminum alloys, nickel alloys, copper alloys, and lead.

A set of known aging mechanisms for metallic cask and internal subcomponents was established by first broadly identifying all potential mechanisms through a review of gap assessments for DSSs, technical literature, and operating experience from nuclear and nonnuclear applications (NRC, 2014, 2010a; Chopra et al., 2014; Hanson et al., 2012; Sindelar et al., 2011; NWTRB, 2010). The known environmental, thermal, mechanical, and irradiation-induced aging mechanisms are as follows:

- general corrosion
- pitting and crevice corrosion
- galvanic corrosion
- MIC
- SCC (including hydrogen embrittlement)
- creep
- fatigue
- thermal aging
- radiation embrittlement
- stress relaxation
- wear

Not all of these mechanisms are considered to be credible for each structure, system, and component (SSC). For example, temperatures are not considered sufficiently high to cause creep of steel and stainless steel subcomponents. Also, general corrosion is not considered to be a credible aging mechanism for subcomponents fabricated from stainless steels, because these materials exhibit passive behavior and negligible general corrosion rates. Detailed discussions regarding potential aging mechanisms for each material and the technical bases for those requiring aging management follow.

3.2.1 Steel (carbon, low-alloy, high-strength low-alloy)

In DSSs, steel subcomponents are commonly used and are exposed to sheltered environments, outdoor air, helium, demineralized water, and groundwater or soil, and also may be embedded in concrete or neutron-shielding materials. The exterior surfaces of some steel subcomponents are coated with epoxy or inorganic zinc to mitigate corrosion; however, these coatings can degrade, resulting in exposure of steel to the atmosphere. Steels used to construct transfer casks are predominately exposed to an indoor environment, except for short periods of outdoor exposure during transfer operations. For such air-indoor/outdoor environment exposure, aging effects from aqueous corrosion processes are expected to be bounded by the outdoor environment. As such, the indoor air environment is not discussed separately.

3.2.1.1 General corrosion

General corrosion, also known as uniform corrosion, proceeds at approximately the same rate over a metal surface (Phull, 2003b). Freely exposed steel surfaces in contact with moist air or water are subject to general corrosion. The corrosion rate depends on solution composition, pH, and temperature. The iron Pourbaix diagram shows that iron undergoes active corrosion forming Fe^{2+} or Fe^{3+} ions at pH values lower than 8.5 to 9 (Kodama, 2005). At higher values of pH, iron can be passive, leading to a very low corrosion rate.

Steel subcomponents exposed to outdoor and sheltered environments

If steel is placed in a completely dry atmosphere, oxide film growth is so small that the corrosion rate is virtually negligible. However, in outdoor conditions, rain, fog, snow, and dew condensation can generate moisture layers on the steel surface that cause general corrosion. Atmospheric corrosion rates can vary from 0 to 0.2 millimeters/year (mm/yr) [0 to 7.9 mils/yr] depending on relative humidity, temperature, and levels of chloride and pollutants in the atmosphere (NACE, 2002). Rates can be more significant in industrial and marine environments (McCuen and Albrecht, 1994).

In a sheltered environment, deliquescence of airborne salts below the dew point also could generate an aqueous electrolyte initiating general corrosion. These salts may be chloride rich and originate from marine environments, deicing salts, and condensed water from cooling towers, as well as a range of other nonchloride-rich species originating from industrial, agricultural, and commercial activities. Studies have shown that $MgCl_2$, a component of sea salt with a low deliquescence relative humidity, would deliquesce below 52 degrees C [126 degrees F] under realistic absolute humidities in nature (He et al., 2014). The heat generated by the radioactive decay of spent fuel decreases over time. Time-temperature profiles calculated for the stainless steel canister shell suggest that, while initial temperatures are high, the threshold temperature for deliquescence of some salts on the external surface of the shell could be reached during the 60-year timeframe (EPRI, 2006; Meyer et al., 2013).

Because steel subcomponents exposed to sheltered environments are usually located farther away from the fuel compared to the stainless steel canister shell, they are expected to reach these threshold temperatures for deliquescence at an earlier time. As such, the potential for general corrosion of steel subcomponents exposed to a sheltered environment is present.

Because aqueous electrolytes initiating general corrosion of steels exposed to outdoor and sheltered environments are potentially present, and corrosion rates may be sufficient to affect component intended functions, general corrosion is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Steel subcomponents exposed to demineralized water

Demineralized water is used in the steel water jacket of some transfer casks for radiation shielding. In some cases, 25-percent ethylene glycol is added to the water to decrease the freezing point, and this is expected to decrease the corrosivity of water (van Bodegom et al., 1987). The iron Pourbaix diagram shows that iron undergoes active corrosion at neutral pH, as long as water is present (Kodama, 2005). The corrosion rate for iron is approximately

0.1 mm/yr [3.9 mils/yr] in stagnant fresh water at atmospheric temperatures (Kodama, 2005). In 60 years of continuous exposure in such water, the material thinning is expected to be approximately 6 mm [0.2 in]. This is a conservative estimate of the corrosion of steel water jackets, as the jackets are not necessarily filled when the transfer cask is not in use. However, general corrosion of steels exposed to demineralized water is nonetheless considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Steel subcomponents exposed to groundwater or soil

The corrosion rate of steel in groundwater or soil depends on many factors, such as the oxygen level; resistivity; pH, buffer capacity; redox potential; and the presence of chlorides, sulfides, neutral salts, and sulfates. Soils may be acidic, neutral, or alkaline, with pH values typically ranging from 4.5–8.5 (Kodama, 2005), which is in the range of active corrosion discussed previously. Corrosion rate data for iron artifacts buried in soil show that most corrosion rates are 0.1 to 10 micrometers (μm)/yr [0.004 to 0.4 mils/yr], despite the variety of artifacts in terms of origin and environmental conditions (David et al, 2002). In 60 years of continuous soil exposure, the material thinning is expected to be approximately 0.006 to 3.6 mm [0.2 to 142 mils]. As such, general corrosion of steels exposed to groundwater or soil is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Steel subcomponents exposed to an embedded (concrete) environment

In overpacks, some steel subcomponents are embedded in concrete. The concrete is in contact with air or soil. When the concrete is intact, the alkaline concrete solution passivates the steel. As concrete degrades with time, embedded steel can be exposed to water containing dissolved carbonates and chlorides, and general corrosion can be significant, as discussed previously. As such, general corrosion of steels exposed to an embedded (concrete) environment is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Steel subcomponents exposed to an embedded (neutron-shielding) environment

In DSSs, some polymer-based, neutron-shielding materials are poured into a steel structure, leaving one side of the steel embedded. The neutron-shielding materials include Holtite™ and BISCO NS-3. Because the embedded side of the steel has limited exposure to water and oxygen, general corrosion is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Steel subcomponents exposed to helium

As mentioned previously, the iron Pourbaix diagram shows that iron undergoes active corrosion at neutral pH as long as water is present (Kodama, 2005). However, there is very little residual water in internal environments following drying and refilling with inert gas, and thus the corrosion reaction with steel will be limited. Jung et al. (2013) show that the relative humidity inside the system after drying is no more than 5 percent at the beginning of storage and is less than 0.5 percent in 60 years. Furthermore, some steel subcomponents are coated by aluminum or electroless nickel, which are more corrosion resistant than steel. As such, general corrosion of steel exposed to helium is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.1.2 Pitting and crevice corrosion

Pitting corrosion is a localized form of corrosion that is confined to a point or small area of a metal surface (Frankel, 2003). It takes the form of cavities called pits. Crevice corrosion is another localized form of corrosion that occurs in a wetted environment when a crevice exists (Kelly, 2003). It occurs more frequently in connections, lap joints, splice plates, bolt threads, under bolt heads, or at points of contact between metals and nonmetals. Crevice corrosion is associated with stagnant or low-flow solutions. As discussed previously, the common form of corrosion for steel is general corrosion. However, steel is also known to be susceptible to pitting and crevice corrosion in an oxidizing and alkaline environment, especially in the presence of chlorides. The exterior surfaces of some subcomponents are coated with epoxy or inorganic zinc to mitigate corrosion (e.g., the outer shell of the bolted cask system). Depending on the quality and chemical composition of the coating, water and corrosive agents can permeate coating defects, initiating pitting. After initiation of a coating defect, the coating could function as a crevice former and initiate crevice corrosion.

Steel subcomponents exposed to outdoor and sheltered environments, demineralized water, groundwater or soil, and embedded (concrete) environments

As discussed in Section 3.2.1.1, the potential to form aqueous electrolytes on surfaces exposed to outdoor and sheltered environments is present, either via direct exposure to precipitation or through deliquescence of deposited salts. These electrolytes, demineralized water, and groundwater or soil could be conducive to pitting and crevice corrosion of steel. For steel embedded in concrete, as concrete degrades with time, steel can be exposed to water containing dissolved carbonates and chlorides, which could be conducive to pitting and crevice corrosion as well.

Localized corrosion of steels is attributed to the presence of macro-galvanic cells, where local differences in electrochemical potential are created by conditions such as chemical composition differences within the steel matrix, discontinuous surface films (e.g., mill scale), and differences in oxygen supply (Revie, 2000).

Because steel subcomponents exposed to outdoor and sheltered environments are likely to come into contact with aqueous electrolytes, and the localized corrosion in these environments is possible, loss of material due to pitting and crevice corrosion is considered to be credible. Therefore, aging management is required during the 60-year timeframe.

Steel subcomponents exposed to embedded (neutron-shielding materials) environments

Because of the limited water and oxygen in embedded environments, pitting and crevice corrosion are not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Steel subcomponents exposed to helium

Inside DSSs, there is very little residual water following drying, and thus the corrosion reaction with steel will be limited. Jung et al. (2013) show that the relative humidity inside the system is no more than 5 percent at the beginning of storage and is less than 0.5 percent in 60 years. Furthermore, some steel subcomponents are coated by aluminum or electroless nickel, which are more corrosion resistant than steel. As such, localized corrosion of steel exposed to helium is considered to be insignificant, and therefore, aging management is not required during the 60-year timeframe, regardless of the coating.

3.2.1.3 Galvanic corrosion

Galvanic corrosion occurs when two dissimilar metals or conductive materials are in physical contact in the presence of a conducting solution (Baboian, 2003; Hack, 1993). Under these conditions, an electrolytic cell is formed, transmitting an electrical current between an anode (i.e., less noble material) and a cathode (i.e., more noble material). Oxidation occurs at the anode, and reduction occurs at the cathode. The relative nobility of different materials has been most commonly constructed from measurements in seawater (Baboian, 2003). With certain exceptions, it is broadly applicable to other natural waters and in uncontaminated atmospheres. It is used here to infer the relative nobility of the canister materials during extended storage (e.g., steel is less noble than stainless steel, graphite, nickel, and brass). The extent of galvanic corrosion depends on potential differences between the two metals, surface area ratio of the anode and cathode, environment, reaction kinetics, corrosion products, and other factors (Baboian, 2003). In DSSs, galvanic coupling exists between steel and other more noble materials such as stainless steel, graphite, nickel, and brass. These galvanic couples can be exposed to sheltered and outdoor air environments.

Steel subcomponents exposed to outdoor and sheltered environments

Aqueous electrolytes for subcomponents exposed to outdoor and sheltered environments are present during the 60-year timeframe. Because these electrolytes could initiate steel corrosion, and corrosion of steel is expected to be enhanced under galvanic coupling, loss of material due to galvanic corrosion of steel is considered to be credible in dissimilar metal couples, and therefore, aging management is required during the 60-year timeframe.

3.2.1.4 Microbiologically influenced corrosion

MIC is corrosion caused or promoted by the metabolic activity of microorganisms (Dexter, 2003). Active microbial metabolism requires water in the form of water vapor, condensation, or deliquescence, and available nutrients to support microbial activity (Horn and Meike, 1995). Biofilms can form even under radiation environments (Bruhn et al., 2009). Bacteria resistant to radiation include *Micrococcus radiodurans*, which can tolerate 10 kilograys (kGy) [10^6 rads] of irradiation. MIC is limited where relative humidity is below 90 percent and negligible for relative humidity below 60 percent (King, 2009). MIC has been found to be operable within a temperature range of −5 degrees C to 110 degrees C [23 to 230 degrees F].

Several types of microbes can exist within a biofilm. For instance, sulfate-reducing bacteria are of primary concern in wet, cool, and anoxic environments (Little and Wagner, 1996). Another type of microbe is the acid-producing bacteria, which can promote depassivation of oxide films on metals. Other types of bacteria are created by ammonia production, metal deposition, and hydrogen production (Walch and Mitchell, 1983; Little and Wagner, 1996). Although most of the evidence of MIC for metallic components is from conditions under which the metal surface is kept continuously wet, microorganisms can live in many environments, such as water, soil, and air, where aerobic bacteria (e.g., iron-manganese oxidizing bacteria, sulfur/sulfide oxidizing bacteria, methane producers, organic acid-producing bacteria), fungi, and algae can develop. This is borne out by research studies on MIC in soils (Jack et al., 1996) and in tropical environments (Caprio et al., 1995).

Steel subcomponents exposed to groundwater/soil and embedded (concrete) environments

For soils, MIC rates for steel and iron have been correlated with the pH, oxidation reduction potential, resistivity, and water content of the soil, as well as with the type of soil. Moist, aerobic soils, where oxygen can readily reach exposed steel, show MIC rates typically in the range of 0.04 to 0.2 mm/yr [2 to 8 mils/yr] (Jack et al., 1996). Anaerobic soil environments show intermediate MIC rates of steel on the order of 0.002 to 0.01 mm/yr [0.08 to 0.3 mils/yr]. Typical MIC rates of metal loss for unprotected line pipe steel in a sulfate-reducing bacteria/FeS environment are 0.2 mm/yr [8 mils/yr] for general corrosion and 0.7 mm/yr [28 mils/yr] for pitting corrosion. When steel is embedded in concrete, it can be exposed to groundwater or soil, as concrete degrades with time, which could be conducive to MIC as well. As such, MIC of steel in soil and concrete environments is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Steel subcomponents exposed to sheltered and outdoor environments

As discussed in Section 3.2.1.1, the potential to form aqueous electrolytes for subcomponents exposed to outdoor and sheltered environments is present, either from direct exposure to precipitation or by deliquescence of deposited salts. These electrolytes have the potential to support microbial activity.

A limited number of research studies have shown that MIC may occur on steel surfaces exposed to tropical and polluted atmospheric conditions (Caprio et al., 1995; Parra et al., 1996; Maruthamuthu et al., 2008). However, there is no operating experience of MIC degradation of steel engineering components that are exposed to environments similar to those of dry cask storage systems, where continuous exposure to a relative humidity above 90 percent is not expected. The operating experience of MIC for metallic components is largely from instances in which the metal surface was kept continuously wet. Because there is no applicable operating experience of MIC damage of steel under relevant atmospheric conditions, MIC is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Steel subcomponents exposed to demineralized water

The transfer cask water jackets are filled with demineralized water and drained during each loading campaign. If any bacteria are introduced during these operations, the concentration is expected to be insignificant. Microbial metabolism and growth depends upon adequate supplies of essential macro and micro nutrients. Critical nutrients, such as carbon, nitrogen, and phosphorous, must be present in appropriate concentrations (Dragun, 1988). It is expected that the concentrations of these species in demineralized water are well below the critical values. As such, MIC of steel in this environment is considered to be insignificant, and therefore, aging management is not required during the 60-year timeframe.

Steel subcomponents exposed to helium and embedded (neutron shielding) environments

Because of the limited amount of water and nutrients in the helium environments within casks and canisters, and the limited water in embedded environments, MIC of steel is not credible for the 60-year timeframe, and therefore, aging management is not required.

3.2.1.5 Stress corrosion cracking

SCC is the cracking of a metal produced by the combined action of corrosion and tensile stress (applied or residual) (Jones, 1992). SCC is highly chemical specific in that certain alloys are likely to undergo SCC only when exposed to a small number of chemical environments. SCC is the result of a combination of three factors: (1) a susceptible material, (2) exposure to a corrosive environment, and (3) tensile stresses. High-strength steels with yield strengths greater than or equal to 150,000 pounds per square inch [150 ksi] have been found to be susceptible to SCC under exposure to aqueous electrolytes, particularly when containing H_2S) (Jones, 2003; McMahon, 2001; EPRI, 2007).

Steel subcomponents exposed to sheltered and outdoor environments

In DSSs, some steels with moderately high strength are used as bolting material, such as the lid bolts for the direct-load bolted cask systems. These steel subcomponents are exposed to sheltered and outdoor environments, and thus an aqueous electrolyte necessary to support SCC could be present.

SCC also requires the presence of a sufficient tensile stress. Calculations using the approach proposed by Baggerly (1999) show that the stress threshold to initiate SCC of steel bolts is usually larger than 70 percent of the bolting material's minimum yield strength, while the Electric Power Research Institute (EPRI, 2007) states that stresses near the yield strength are required to initiate SCC. The high-strength steel bolting in DSSs is expected to be loaded to stresses much lower than these SCC thresholds. For example, under normal conditions, the stress experienced by the lid bolts of bolted cask systems is primarily from the bolt preload applied to seat, or engage, the lid gaskets, and these preloads are well below the bolting material's yield strength. Also, in the Standardized NUHOMS system, the high-strength structural bolts in the horizontal storage module (HSM) are installed “snug tight” and are not loaded close to critical stresses.

Because of the low applied stresses, SCC of steel bolts exposed to sheltered and outdoor environments is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.1.6 Creep

Creep is the time-dependent inelastic deformation that takes place at an elevated temperature and a constant stress (Gibeling, 2000). Because the deformation processes that produce creep are thermally activated, the rate of this time-dependent deformation is a strong function of the temperature. The creep rate also depends on the applied stress but does not generally vary with the environment. As a general rule of thumb, at temperatures below $0.4T_m$, where T_m is the melting point of the metal in Kelvin (K), thermal activation is insufficient to produce significant creep (Cadek, 1988). With a melting point of 1,789 K (1,516 degrees C [2,760 degrees F]), temperatures of at least 716 K (443 degrees C [829 degrees F]) are required to initiate creep in steels. However, the $0.4T_m$ rule of thumb underestimates the minimum creep temperature for steels, as temperatures above 500 degrees C [932 degrees F] have been found to be required for creep in steels (Samuels, 1988).

Steel subcomponents exposed to helium

The highest temperatures within the DSSs are at locations close to the fuel rods. The maximum expected temperature of fuel cladding has been estimated to be 400 degrees C [752 degrees F] at the beginning of storage (Jung et. al., 2013). This cladding temperature is expected to decrease to around 266 degrees C [510 degrees F] after 20 years and to approximately 127 degrees C [261 degrees F] after 60 years. These estimates depend on many factors, such as the initial heat load of the SNF. Because the fuel rods are the only heat source within the system, these temperatures provide upper temperature limits for all subcomponents. It is apparent from these temperatures that internal subcomponents will not approach the minimum 500 degrees C [932 degrees F] temperature that has been found to be required for significant creep to occur in steels. Hence, creep of steel internals exposed to helium is not expected to be credible, and therefore, aging management is not required during the 60-year timeframe.

Steel subcomponents exposed to sheltered, outdoor air, demineralized water, groundwater or soil, and embedded (all) environments

Because steel subcomponents exposed to sheltered, outdoor air, demineralized water, groundwater or soil, and embedded environments experience significantly lower temperatures than those experienced by the internal subcomponents, creep of these steel subcomponents is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.1.7 Fatigue

Fatigue is the progressive structural damage that occurs when a metal is subjected to cyclic loading (Hoeppner, 1996). Because spent fuel storage is a static application, cyclic loading by a purely mechanical means is largely limited to transfer cask lifting trunnions, which are loaded each time a canister is moved from the spent fuel pool to the dry storage pad. Other subcomponents, however, could experience cyclic loads due to thermal effects.

The reviewer should review all fatigue analyses contained in the applicant’s design basis documents to determine whether the renewal application adequately addresses the implications of extending the operating period to 60 years. This re-examination of the original fatigue analyses are defined as TLAAs.

As described in greater detail in Chapter 5 of this report, the reviewer should review the design codes and standards to identify any required fatigue analyses and ensure that the applicant addresses those analyses with a TLAA. For example, components that were designed in accordance with the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Section III, Division 1, Subsections NB or NC (ASME, 2007a) were evaluated for the effects of cyclic loading per subparagraphs NB-3222.4 and NC-3219.2, respectively. Also, the designs of some steel support structures may be performed in accordance with the American Institute of Steel Construction (AISC) Standard 360, “Specifications for Structural Steel Buildings” (AISC, 2010). Appendix 3 of AISC 360, “Design for Fatigue,” provides criteria for the evaluation of cyclic loading.

The staff’s guidance for the review of TLAAs is provided in NUREG–1927, Revision 1, and Chapter 5 of this report. In its evaluation of a TLAA, an applicant may conclude that an analysis can no longer support a determination that aging will not adversely affect an important-to-safety function in the 60-year timeframe of the period of extended operation. In that case, the applicant may manage the aging of the associated SCC with an AMP.

The AMR tables in Chapter 4 recommend that applicants address any applicable TLAAs associated with components with a structural function. If no fatigue analysis was performed in support of the component design, no action is required of the applicant.

3.2.1.8 Thermal aging

The microstructures of most steels will change, given sufficient time at temperature, and this can affect mechanical properties. This process is commonly called thermal aging. The effect of thermal aging will depend on the time at temperature and the microstructure and carbon content of the steel subcomponents.

Steel subcomponents exposed to helium

The maximum expected temperature of fuel cladding has been estimated to be 400 degrees C [752 degrees F] at the beginning of storage (Jung et. al., 2013). This upper-bound cladding temperature is expected to decrease to around 266 degrees C [510 degrees F] after 20 years and to approximately 127 degrees C [261 degrees F] after 60 years. Although the temperature of steel components within the cask internal environment will be lower than that of the fuel cladding, consideration of the cladding temperatures provides a conservative estimate of the effects of thermal aging.

Carbon steels in the normalized condition (ferrite/pearlite microstructures) are commonly used in the petroleum and chemical industry with exposure temperatures similar to those in DSS internal environments, approximately 400 degrees C [752 degrees F] and lower (ASM International, 1998). ASME Code Section II, Part D, provides allowable operating stresses for carbon steels at these temperatures (ASME, 2007b).

The ASME Code also provides for the use of hardened (quenched and tempered) alloy steels at temperatures typically expected within storage systems during the 20- to 60-year period of extended operation. For example, ASME type SA-537 Grade 2 alloy steel receives a tempering heat treatment of at least 595 degrees C [1,100 degrees F] following quenching, and the ASME Code provides allowable operating stresses up to 371 degrees C [700 degrees F]. This compares to the estimated upper-bound 266 degrees C [510 degrees F] temperature during the period of extended operation. Some hardened alloy steels can experience reductions in fracture toughness when tempered at temperatures greater than 200 degrees C [392 degrees F]. The degree of the reduction in toughness depends on the carbon content and the tempering conditions that were employed during processing (Krauss, 2005).

The effects of elevated storage temperatures on material properties are evaluated during the initial license application (typically first 20 years of storage). Although the temperatures inside the canister after 20 years may still have the capacity to alter mechanical properties, it is likely that the steel tempering that occurs during manufacture and the higher temperatures present during the initial storage period would dominate any effects of tempering at the lower temperatures during the period of extended operation.

It can thus be concluded that thermal aging generally is not expected to produce degradation of the mechanical properties of steels in the period of extended operation, and therefore, aging management is not required during the 60-year timeframe. Nevertheless, the reviewer should verify this conclusion on a case-by-case basis.

Steel subcomponents exposed to sheltered, outdoor air, demineralized water, groundwater or soil, and embedded (all) environments

As stated above, undesired material property changes due to tempering of hardened steels could occur at temperatures greater than 200 degrees C [392 degrees F]. The temperatures of steel subcomponents exposed to sheltered, outdoor air, demineralized water, groundwater or soil, and embedded environments are bounded by the stainless steel canister shell temperature, because these subcomponents are located farther away from the fuel. Time-temperature profiles calculated for the stainless steel canister shell estimate that the peak temperature is below 200 degrees C [392 degrees F] (EPRI, 2006; Meyer et al., 2013). Because the peak temperatures for steel subcomponents exposed to sheltered, outdoor air, demineralized water, and embedded environments are below the temperature required to cause reductions in toughness, thermal aging is not considered to be credible for these subcomponents, and therefore, aging management is not required during the 60-year timeframe.

3.2.1.9 Radiation embrittlement

Embrittlement of metals may occur under exposure to neutron radiation. Depending on the neutron fluence, radiation can cause changes in mechanical properties, such as loss of ductility, reduced fracture toughness, and decreased resistance to cracking.

Neutron irradiation has the potential to increase the tensile and yield strength and decrease the toughness of carbon and alloy steels (Nikolaev et al., 2002). Neutron fluence levels greater than 10^{19} neutrons/square centimeter (n/cm^2) [6.5×10^{19} n/in^2] are required to produce a measureable degradation of the mechanical properties (Nikolaev et al., 2002; Odette and Lucas, 2001).

For dry cask storage, a neutron flux of 10^4–10^6 n/cm^2-s [6.5×10^4–6.5×10^6 n/in^2-s] is typical (Sindelar et al., 2011). At these flux levels, the accumulated neutron fluence after 60 years is about 10^{13}–10^{15} n/cm^2 [6.5×10^{13}–6.5×10^{15} n/in^2]. To verify the conservatism of this estimate, the NRC staff performed an independent calculation of the maximum potential accumulated neutron fluence on DSS components. The staff considered components most directly exposed to the radiation source (middle of the fuel basket) and assumed fuel is loaded immediately after it is removed from the reactor vessel and stored for 100 years. To further provide a bounding estimate, the staff assumed a cask design that uses 40 Westinghouse 17×17 PWR fuel assembles with an average burnup of 70 GWd/MTU and 4.0 fuel enrichment. The staff calculated the neutron source term for neutrons with energy at or greater than 1 MeV using the Origen/Arp computer code of the SCALE 6.1 computer code system. At this location, the total accumulated neutron fluence after 100 years of storage was calculated to be 2.63×10^{16} n/cm^2 [1.70×10^{17} n/in^2]. This worst-case estimate is greater than that calculated using the flux levels reported in Sindelar, however, the NRC estimated fluence level is still three orders of magnitude below the levels reported to degrade the fracture resistance of carbon and alloy steels.

Thus, radiation embrittlement of steel exposed to any environment is not a credible aging mechanism, and therefore, aging management is not required during the 60 year timeframe.

3.2.1.10 Stress relaxation

Stress relaxation of bolting or other tightening subcomponents is the steady loss of elastic stress in a loaded part due to atomic movement at elevated temperature (Earthman, 2000). It results in a loss of clamping forces or preload in a heavily loaded joint. In the stress relaxation process, the total strain is constant and the stress reduction at constant temperature occurs as an elastic strain is converted to an inelastic strain. Stress relaxation is a strong function of temperature and bolt material. It also depends on geometry of the bolt and thread quality (Sachs and Evans, 1973). It decreases with time, as the tensile stress in the bolt decreases (Kulak et al., 2001). Steel bolting is used in several DSS applications in sheltered and outdoor environments, such as in the NUHOMS canister support structure and the HI-STORM overpack lid.

Steel subcomponents exposed to sheltered environments

Bickford (2008) demonstrated that the residual stress of carbon steel bolts due to relaxation is about 85 percent of the initial applied stress at temperatures greater than about 100 degrees C [212 degrees F]. Meyer et al. (2013) show that the external surface temperature of storage canisters can be greater than 200 degrees C [392 degrees F] at the beginning of the storage period. Thus, stress relaxation of steel bolting exposed to sheltered environments adjacent to the canister is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Steel subcomponents exposed to outdoor environments

Bolting in outdoor environments is not considered to be exposed to sufficiently high temperatures to cause stress relaxation. Similarly, transfer cask bolting in indoor/outdoor environments is not considered to be exposed to high temperatures for a sufficient amount of time to cause stress relaxation. Thus, for steel bolting exposed to outdoor environments, aging management is not required during the 60-year timeframe.

3.2.1.11 Wear

Rolling contact wear results from the repeated mechanical stressing of the surface of a body rolling on another body (Blau, 1992). For the HI-TRAC transfer cask exposed to indoor and outdoor air, ASME SA36 steel is used to construct the transfer lid wheel track, which could experience rolling contact during SNF loading and unloading operations. Thus, wear of these steel subcomponents is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

3.2.2 Stainless steel

Austenitic, ferritic, martensitic, duplex, and precipitation-hardened stainless steels are used in constructing DSS subcomponents. They are exposed to outdoor, sheltered, embedded, helium, and demineralized water environments. Some stainless steels are used to construct the transfer cask, which is predominately exposed to an indoor environment or otherwise encased without direct air ingress, except for short periods of air exposure during transfer operations. For such air-indoor/outdoor environments, the aging mechanisms from aqueous corrosion processes are expected to be bound by the outdoor environment, because it is more corrosive. As such, the indoor air environment is only discussed separately for the evaluation of SCC, where periodic rinsing of the transfer cask external surfaces is expected to minimize halide deposition.

3.2.2.1 General corrosion

Stainless steels exhibit passive behavior in all DSS environments, resulting in negligible general corrosion rates (Grubb, 2005). As such, general corrosion of stainless steel exposed to all environments is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.2.2 Pitting and crevice corrosion

As discussed in Section 3.2.1.2, pitting corrosion is a localized form of corrosion that is confined to a point or small area of a metal surface (Frankel, 2003), and crevice corrosion occurs in a wetted environment when a crevice exists that allows a corrosive environment to develop in a component (Kelly, 2003). In DSSs, crevice corrosion may occur (i) where the canister contacts the support rails for horizontal canister designs and (ii) between canister and guide rails or the support pedestal in some vertical designs. Stainless steels are susceptible to pitting and crevice corrosion, with chloride being the most common agent for initiation (Grubb et al., 2005). Other halides, notably bromides, and hypochlorites are also initiation agents (EPRI, 2007).

<u>Stainless steel subcomponents exposed to outdoor and sheltered environments</u>

As discussed in Section 3.2.1.1, the potential to form aqueous electrolytes for subcomponents exposed to outdoor and sheltered environments is present, either via direct exposure to precipitation or by deliquescence of deposited salts. These electrolytes could be conducive to pitting and crevice corrosion of stainless steel. Atmospheric corrosion of stainless steels typically proceeds in the form of localized corrosion (Cook et al., 2010; Shirai et al., 2011; Tani et al., 2009). However, experimentally measured penetration rates for pitting and crevice corrosion are quite low. Stainless steel exposed to a saturated NaCl steam mist at 60 degrees C [140 degrees F] and 95 percent relative humidity (NWTRB, 2010) yielded maximum penetration rates of 0.02 mm/yr [8 mils/yr] for pitting and 0.03 mm/yr [11 mils/yr] for crevice corrosion. These maximum rates suggest that penetration of a 15-mm [0.59-in]-thick canister wall by pitting or crevice corrosion would require 750 years and 495 years, respectively. Davison et al. (1987) reported pitting penetration of 0.028 mm [1.1 mils] after 15 years, which yields a penetration rate of 0.0019 mm/yr [0.075 mils/yr]. Using the penetration depth versus time equation in Eq. (3.2-1) from NRC (2014):

$$d = At^{-n} \text{ and } n = 0.33 \text{ to } 0.5, \qquad (3.2\text{-}1)$$

the penetration rate in Davison et al. (1987), and n = 0.5 yields a penetration time for a 15-mm [0.59-in]-thick canister wall of 19,000 years. Based on these penetration rates, the canister wall would not be penetrated in the 60-year timeframe. The rate of pit propagation can be much higher in aggressive environments. Morrison (1972) reported pit penetrations exceeding 0.5 mm [20 mils] in 304 and 316 stainless steels after a 28-month exposure at the Kennedy Space Center, Florida. However, the pitting rates measured under aggressive marine environments would require more than 250 years to penetrate 12.7-mm [0.5-in]-thick stainless steel. Hence, neither pitting nor crevice corrosion itself is expected to produce damage to the stainless steel subcomponents in the 60-year timeframe.

However, both pitting and crevice corrosion are known to be precursors to SCC. He et al. (2014) observed that all the SCC cracks started at the bottom of the pits. Therefore, pitting and crevice corrosion are also considered to be credible during the 60-year timeframe, due to their role as precursors to atmospheric SCC, and aging management is required accordingly.

Stainless steel subcomponents exposed to helium, demineralized water, and embedded (all) environments

Stainless steel exposed to helium and demineralized water is not susceptible to pitting and crevice corrosion due to the lack of halides. Because of limited water and oxygen, stainless steel is also not susceptible to pitting and crevice corrosion in embedded environments. As such, pitting and crevice corrosion of stainless steel exposed to helium, demineralized water, and embedded environments are not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.2.3 Galvanic corrosion

As discussed in Section 3.2.1.3, galvanic corrosion occurs when two dissimilar metals or conductive materials are in physical contact in the presence of a conducting solution (Baboian, 2003; Hack, 1993). In DSSs, graphite is used to lubricate stainless steel subcomponents such as the stainless steel upper trunnion for the TN-68 bolted cask and the interface between the NUHOMS canister shell and support structure, resulting in galvanic contact between stainless steel and graphite. Because graphite is strongly cathodic and the contact is close, the galvanic coupling effect is expected to be strong. These galvanic couples are exposed to sheltered and outdoor environments.

Because these electrolytes conducive to galvanic corrosion exist in both sheltered and outdoor environments, galvanic corrosion of stainless steel in contact with graphite lubricants is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

3.2.2.4 Microbiologically influenced corrosion

As discussed in Section 3.2.1.4, MIC is caused or promoted by the metabolic activity of microorganisms (Dexter, 2003). Microorganisms can live in many environments, such as water, soil, and air, where aerobic bacteria (e.g., iron-manganese oxidizing bacteria, sulfur/sulfide oxidizing bacteria, methane producers, organic acid-producing bacteria), fungi, and algae can develop.

Stainless steel subcomponents exposed to sheltered and outdoor environments

As discussed in Section 3.2.1.1, the potential to form aqueous electrolytes for subcomponents exposed to outdoor and sheltered environments is present during the 60-year timeframe, either from direct exposure to precipitation or by deliquescence of deposited salts. These electrolytes could support microbial activity; however, there has not yet been any operating experience of MIC in atmospheric environments where stainless steel surfaces are only intermittently wetted. Due to the absence of any operating experience of MIC damage of stainless steel under atmospheric conditions, MIC is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Stainless steel subcomponents exposed to demineralized water

The transfer cask water jackets are filled with demineralized water and drained during each loading campaign. If any bacteria are introduced during these operations, the concentration is expected to be insignificant. Microbial metabolism and growth depends upon adequate supplies of essential macro and micro nutrients. Critical nutrients such as carbon, nitrogen, and phosphorous must be present in appropriate concentrations (Dragun, 1988). It is expected that the concentrations of these species in demineralized water are well below the critical values. As such, MIC of stainless steel exposed to demineralized water is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Stainless steel subcomponents exposed to helium and embedded (all) environments

Because of the limited amount of water and nutrients in the helium environments within casks and canisters, and the limited water in embedded environments, MIC of stainless steel is not credible for the 60-year timeframe, and therefore, aging management is not required.

3.2.2.5 Stress corrosion cracking

SCC is the cracking of a metal produced by the combined action of corrosion and tensile stress and is highly chemical specific (Jones, 1992, 2003). Most ferritic and duplex stainless steels are either immune or highly resistant to SCC; however, all austenitic grades, especially Types 304, 304L, 304LN, 316, 316L, and 316LN, have long been reported in the literature to be susceptible to chloride-induced SCC in the normal wrought condition (Grubb et al., 2005; Morgan, 1980; Kain, 1990). This susceptibility increases when the material is sensitized (He et al., 2014). In the welded condition, the heat-affected zone, which is a thin band located adjacent to the weld, can be sensitized by the precipitation of carbides that extract chromium out of the metal matrix.

The Electric Power Research Institute (EPRI, 2005, 2006) and the Nuclear Decommissioning Authority in the United Kingdom (Nuclear Decommissioning Authority, 2007) published review reports on SCC of stainless steel. More recently, the NRC released Information Notice (IN) 2012-20, “Potential for Chloride-Induced Stress Corrosion Cracking of Austenitic Stainless Steel and Maintenance of Dry Cask Storage Systems” (NRC, 2012). The IN describes several incidents in commercial nuclear power plants where SCC of austenitic stainless steel components was attributed to atmospheric chloride exposure (NRC, 1999, 2010c; FPL, 2005; Alexander et al., 2010). These events involved components such as emergency core cooling system piping, SNF pool cooling lines, and outdoor tanks. The IN notes that chlorides may be present in the atmosphere, not only in marine environments but also near cooling towers, salted roads, or other locations. The susceptibility of austenitic stainless steels to SCC tends to increase as the chloride concentration in the solution increases, but the level of chlorides required to produce SCC is very low and is dependent on the type of chloride salts present. The material is more resistant to SCC in NaCl solutions but cracks readily in $MgCl_2$ solutions (Grubb et al., 2005). Increased temperature and the presence of oxygen tend to aggravate chloride-induced SCC.

Stainless steel subcomponents exposed to outdoor and sheltered environments

As discussed in Section 3.2.1.1, the potential to form electrolytes for subcomponents exposed to outdoor and sheltered environments is present, either via direct exposure to precipitation or by deliquescence of deposited salts. These electrolytes could be conducive to SCC of stainless steel. SCC also requires the presence of a tensile stress, which commonly exists at welds originating from fabrication processes, contacts between components, and bolted structures. Fuhr et al. (2013) stated that stresses well below yield can cause SCC and the required stress for SCC initiation decreases as chloride concentration and temperature increase. SCC tests were performed with Type 304L C-ring specimens strained to 0.4 or 1.5 percent (He et al., 2014). At the strain of 0.4 percent, the stress on the C-ring specimen was approximately equal to the material yield stress. SCC initiation was observed on specimens deposited with 1 or 10 grams/square meter (g/m^2) [0.003 or 0.03 ounces/square foot (oz/ft^2)] of simulated sea salt at both strain levels. Constant load tensile tests were performed on Type 304 between 0.5 and 1.75 times the material yield stress (Mayuzumi et al., 2008). Surface chloride concentration was estimated to exceed 10 g/m^2 [0.03 oz/ft^2], while test conditions were 80 degrees C [176 degrees F] at 35 percent relative humidity. Specimens failed at the stress level of 0.5 times the yield stress.

For DSS subcomponents, the stainless steel canister shell is welded. Welds also exist in other subcomponents, such as the cover plates for the vent and drain ports, grapple ring and grapple support, and the Nitronic 60 support rail plate of the NUHOMS system used to support the canister. Fuhr et al. (2013) concluded that the driving stress for SCC of the welded canister is expected to be weld residual stress, considering that the applied stresses are low and residual compressive stresses are believed to be present on the shell outer diameter due to rolling. Their calculations indicate that residual stresses parallel to the weld are tensile through-wall and significantly above the original yield strength of the base metal, while those transverse to the weld are either compressive along the outer canister surface or slightly tensile on the outer diameter but compressive along the midwall. Based on these calculated residual weld stresses, it was concluded that through-wall SCC is most likely to occur transverse to the weld direction. Weld residual stress modeling conducted by the NRC (2013) also indicates that through-wall tensile stresses of sufficient magnitude to support SCC are likely to exist in the weld heat-affected zone.

Because sufficient weld residual stresses and more susceptible material conditions are present near the welds, and aqueous electrolytes conducive to SCC are present in sheltered and outdoor environments, the potential for SCC of the welds in the canister shell and other stainless steel subcomponents is present in the 60-year timeframe. Additionally, the SCC initiation times are relatively short (NWTRB, 2010) with reported crack growth rates of austenitic stainless steels at the weld heat-affected zones ranging from 0.1 mm/yr [3.9 mils/yr] (Hosler, 2010) to 0.67 mm/yr [26.1 mils/yr] (Basson and Wicker, 2002). As a result, through-wall penetration could occur during the 60-year timeframe. This is consistent with the observation of outer-diameter-initiated through-wall SCC in stainless steel piping after 20 to 30 years of exposure in marine environments (Fuhr et al., 2013). As such, atmospheric SCC of stainless steel subcomponents with welds exposed to sheltered and outdoor air is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

For weld-free austenitic stainless steel subcomponents or regions away from welds, such as the canister body, atmospheric SCC is a likely aging mechanism if sufficient stress exists. Its significance and corresponding aging management requirement will need to be assessed case by case, based on applied and residual stresses, operating temperatures, and the presence of chlorides in the environment.

Stainless steel subcomponents exposed to indoor/outdoor environments and demineralized water

Stainless steel transfer casks are exposed to indoor environments during their storage between cask loading campaigns, and thus an aqueous electrolyte is not likely to be present on the transfer cask external surfaces for extended periods. Also, the transfer cask external surfaces are periodically rinsed with demineralized water as they are removed from the spent fuel pool, which would be expected to remove any halides present. As a result, SCC is not considered to be a credible degradation mechanism. In the demineralized water environments of transfer cask neutron shields, SCC is also not considered to be a credible degradation mechanism because of the lack of halides. Therefore, aging management of stainless steel subcomponents exposed to an indoor environment and demineralized water is not required during the 60-year timeframe.

Stainless steel subcomponents exposed to helium and embedded (all) environments

Because of the lack of halides and the small amount of water in helium and embedded environments, SCC of stainless steel is not considered to be credible. Therefore, aging management of stainless steel subcomponents exposed to helium and embedded environments is not required during the 60-year timeframe.

3.2.2.6 Creep

As discussed in Section 3.2.1.6, as a general rule of thumb, thermal activation is insufficient to produce significant creep at temperatures below $0.4T_m$, where T_m is the melting point of the metal in Kelvin (Cadek, 1988). The term “stainless steel” covers a wide range of compositions and microstructures, including austenitic, ferritic, martensitic, duplex, and precipitation hardening stainless steels. This discussion will focus on the austenitic or 300 series stainless steels, because they are most commonly used in DSSs and have the lowest melting point and minimum creep temperature. With a melting point of 1,698 K [1,425 degrees C; 2,597 degrees F], temperatures of at least 679 K [406 degrees C; 763 degrees F] are required to initiate creep in the austenitic stainless steels.

Stainless steel eubcomponents Exposed to helium

The highest temperatures within the DSSs are at locations close to the fuel rods where the environment is helium. The maximum expected temperature of fuel cladding has been estimated to be 400 degrees C [752 degrees F] at the beginning of storage (Jung et. al., 2013). This cladding temperature is expected to decrease to around 266 degrees C [510 degrees F] after 20 years and to approximately 127 degrees C [261 degrees F] after 60 years. These estimates depend on many factors, such as the initial heat load of the SNF. Because the fuel rods are the only heat source within the canister, these temperatures provide upper temperature limits for all subcomponents within the canister. It is apparent from these temperatures that subcomponents within the canister will not reach the 406 degrees C [763 degrees F] minimum temperature that is required for significant creep to occur in austenitic stainless steels. Similarly, significant creep would also not be expected to occur in the other classes of stainless steel, which all have higher minimum creep temperatures. Hence, creep of stainless steel internals exposed to helium is not credible, and therefore, aging management is not required during the 60-year timeframe.

Stainless steel subcomponents exposed to sheltered, outdoor air, demineralized water, and embedded (all) environments

Because stainless steel subcomponents exposed to sheltered, outdoor air, demineralized water, and embedded environments experience significantly lower temperatures than those experienced by the internal subcomponents, creep of these stainless steel subcomponents is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.2.7 Fatigue

As discussed previously in Section 3.2.1.7, because spent fuel storage is a static application, cyclic loading by a purely mechanical means is largely limited to transfer cask lifting trunnions, which are loaded each time a canister is moved from the spent fuel pool to the dry storage pad. Other subcomponents, however, could experience cyclic loads due to thermal effects, such as those caused by daily and seasonal fluctuations in the temperature of the external environment.

The NRC reviewer should review the fatigue analyses contained in the applicant's original design-basis documents to determine whether the renewal application adequately addresses the implications of extending the operating period to 60 years. This reexamination of the original fatigue analyses would typically be defined as TLAAs.

As described in greater detail in Chapter 5 of this report, the reviewer should review the design codes and standards to identify any required fatigue analyses and ensure that the applicant addresses those analyses with a TLAA. For example, components that were designed in accordance with the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Section III, Division 1, Subsections NB or NC (ASME, 2007a) were evaluated for the effects of cyclic loading per subparagraphs NB 3222.4 and NC 3219.2, respectively.

The staff's guidance for the review of TLAAs is provided in NUREG–1927, Revision 1, and Chapter 5 of this report. In its evaluation of a TLAA, an applicant may conclude that an analysis can no longer support a determination that aging will not adversely affect an important-to-safety function in the 60-year timeframe of the period of extended operation. In that case, the applicant may manage the aging of the associated SCC with an AMP.

The AMR tables in Chapter 4 recommend that applicants address any applicable TLAAs associated with components with a structural function. If no fatigue analysis was performed in support of the component design, no action is required of the applicant.

3.2.2.8 Thermal aging

The microstructures of most stainless steels will change, given sufficient time at temperature, and these changes may alter the material's strength and fracture toughness. This process is commonly called thermal aging. For stainless steel subcomponents, the thermal aging process differs for welded and nonwelded subcomponents.

Welded austenitic stainless steel subcomponents exposed to helium

The ferrite present in austenitic stainless steel welds can transform by spinodal decomposition to form Fe-rich alpha and Cr-rich alpha prime phases, and further aging can produce an intermetallic G-phase. The spinodal decomposition and the formation of the intermetallic G-phase takes place during extended exposure to temperatures between 300 and 400 degrees C [572 and 752 degrees F] (Alexander and Nanstad, 1995; Chandra et al., 2012). The maximum expected temperature of fuel cladding has been estimated to be 400 degrees C [752 degrees F] at the beginning of storage (Jung et. al., 2013). This cladding temperature is expected to decrease to around 266 degrees C [510 degrees F] after 20 years and to approximately 127 degrees C [261 degrees F] after 60 years. Based on these temperature estimates, subcomponents located inside the canister and near the fuel could be above the 300 degrees C [572 degrees F] minimum temperature required for these phase changes. Because the phase transformations take place only within the ferrite phase, they increase the hardness and reduce the toughness of the ferrite phase but do not alter the mechanical properties of the austenite phase. Hence, the degree of embrittlement of a weld will depend on a number of factors, including the amount and distribution of ferrite present in the weld and the time spent within the 300 to 400 degrees C [572 and 752 degrees F] temperature range.

Based on Charpy impact toughness testing of cast duplex stainless steels, Kim and Kim (1998) concluded that ferrite levels above 15 percent are required for significant embrittlement, because ferrite resides in discrete islands below this level and does not provide a continuous low-toughness fracture path. Because most welds contain around 4 to 15 percent ferrite (Gavendra et al., 1996), substantial embrittlement of austenitic stainless steel welds is not expected. Gavendra et al. (1996) in NUREG/CR-6428, “Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds,” concluded that thermal aging produced moderate decreases (no more than 25 percent) in the upper shelf Charpy impact energy and relatively small decreases in the fracture toughness of a wide range of austenitic welds. Although the phase changes associated with thermal embrittlement of austenitic stainless steel welds could take place in subcomponents near the fuel within the 60-year timeframe, the minor reductions in fracture toughness that would be produced in the weld indicate that this is not a credible aging mechanism for subcomponents in proximity to the fuel rods, and therefore, aging management is not required.

Subcomponents near the internal wall of a canister or cask would experience temperatures lower than those close to the fuel rods. Time-temperature profiles calculated for a canister surface (EPRI, 2006; Meyer et al., 2013) suggest that maximum canister temperatures would be well below the 300 degrees C [572 degrees F] minimum temperature required for the embrittling phase changes. Hence, thermal aging would not produce any degradation in these subcomponents constructed from austenitic stainless steel, and therefore, aging management is not required during the 60-year timeframe.

Nonwelded austenitic stainless steel subcomponents exposed to helium

Because the phase changes described previously occur only within the ferrite-containing, heat-affected zone of a weld, embrittlement will not occur in austenitic stainless steel subcomponents that do not contain a weld. The only significant thermal aging possible in nonwelded austenitic stainless steels would be a decrease in strength due to a decrease in dislocation density, recrystallization, and an increase in grain size. These processes occur during annealing at temperatures above 1,000 degrees C [1,832 degrees F]. The temperatures of less than 400 degrees C [752 degrees F] that will be experienced by cask internal subcomponents will not degrade nonwelded austenitic stainless steels. Thus, thermal aging of nonwelded austenitic stainless steel is not credible, and therefore, aging management is not required during the 60-year timeframe.

Precipitation-hardened martensitic stainless steel subcomponents exposed to helium

Type 17-4 precipitation-hardened (PH) martensitic stainless steel with Cu and Nb additions is used to construct some fuel basket subcomponents. Operating experience has shown that this material is susceptible to thermal embrittlement, in both welded and nonwelded conditions, at temperatures above 243 degrees C [470 degrees F] (Andresen et al., 2007; Olender et al., 2015; NRC, 2007). The embrittlement mechanism arises from an intra-granular decomposition of the martensitic matrix into two phases, α and α', which are rich in iron and chromium, respectively, and formation of copper rich ε-phase upon further aging. This process leads to an increase in hardness, but decrease in fracture toughness. Olender et al. (2015) reviewed reactor operating experience with 17-4 PH stainless steels. Susceptibility to thermal embrittlement is dependent on several factors including the alloy composition within the allowable specifications, the initial heat treatment and the operating temperature. For operating temperatures between 243 and 316 degrees C [470 to 600 degrees F] Olender et al (2015) recommends an evaluation of conditions on a per-component basis considering operating temperature, exposure time, operating environment, stress levels, and material composition. Above 316 degrees C [600 degrees F] the use of 17-4 PH stainless steel in any condition is not recommended. Subcomponents located inside the canister and near the fuel could be above the temperature threshold for thermal aging. As such, thermal aging of Type 17-4 PH stainless steel is considered to be credible.

Although the above generic evaluation identifies thermal aging of Type 17-4 PH stainless steel as a credible aging mechanism, the degree of embrittlement of a specific SSC will depend on the service temperature and time duration, as well as the initial heat treatment condition of the SSC. As such, a review of the thermal aging effects should be performed on a case-by-case basis for all subcomponents constructed from Type 17-4 PH stainless steel. The reviewer should ensure that the application provides a bounding analysis to show that reduction in mechanical properties due to thermal aging is not expected to compromise the SSC's intended function during the period of extended operation.

Stainless steel subcomponents exposed to sheltered, outdoor, demineralized water, and embedded (all) environments

Because the peak temperatures for stainless steel subcomponents exposed to sheltered, outdoor air, demineralized water, and embedded environments are below the temperature required for the phase changes associated with thermal embrittlement of stainless steels, thermal aging is not considered to be credible for these subcomponents, and therefore, aging management is not required during the 60-year timeframe.

3.2.2.9 Radiation embrittlement

Embrittlement of metals may occur under exposure to neutron radiation. Depending on the neutron fluence, radiation can cause changes in stainless steel mechanical properties, such as loss of ductility, fracture toughness, and resistance to cracking (Was et al., 2006).

Cracking has been observed in boiling-water reactor oxygenated water at fluences above 2 to 5×10^{20} n/cm^2 [1.3 to 3.2×10^{21} n/in^2] (Was et al., 2006). Gamble (2006) found that neutron fluence levels greater than 1×10^{20} n/cm^2 [6.5×10^{20} n/in^2] are required to produce measureable degradation of the mechanical properties. Caskey et al. (1990) also indicates that neutron fluence levels of up to 2×10^{21} n/cm^2 [1.3×10^{22} n/in^2] were not found to enhance SCC susceptibility.

As discussed in Section 3.2.1.9 of this report, the maximum potential accumulated neutron fluence on DSS components after 100 years was calculated to be 2.63 × 10^{16} n/cm^2 [1.70 × 10^{17} n/in^2]. This fluence level is four orders of magnitude below the level that would degrade the mechanical properties of stainless steels. As such, radiation embrittlement of stainless steel exposed to any environment is not credible.

3.2.2.10 Stress relaxation

In DSSs, some stainless steel bolts or screws are used in applications exposed to sheltered and outdoor environments. Section 3.2.1.10 explained that stress relaxation of bolting is the steady loss of stress due to atomic movement at elevated temperature in a loaded part with dimensions that are fixed (Earthman, 2000). The loss of initial applied stress in austenitic stainless steel bolting due to stress relaxation is negligible at temperatures below 300 degrees C [572 degrees F] (Bickford, 2008). This temperature is significantly below those expected in sheltered and outdoor environments. Thus, stress relaxation of stainless steel subcomponents exposed to sheltered and outdoor environments is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.2.11 Wear

Adhesive wear occurs when two metallic components slide against each other under an applied load where no abrasives are present (Magee, 1992). For the NUHOMS transfer cask exposed to indoor and outdoor air, Nitronic® 60 stainless steel (UNS S21800) is used to construct the rails in the cask cavity. The additions of silicon and manganese make this alloy best known for its wear and galling resistance, even in the annealed condition (Magee, 1992). The rails could experience repeated sliding contact over multiple canister transfer operations. Thus, wear of these stainless steel rails is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

3.2.3 Aluminum alloys

In DSSs, aluminum and its 6000 series alloys are commonly used in canister internals to transfer heat because of aluminum’s good thermal conductivity. For example, in the NUHOMS HSM, anodized Al 1100 is used to construct part of the heat shield assemblies, which are exposed to a sheltered environment. In the TN-32 and 68 systems, the lid seal is a double metallic O-ring exposed to a sheltered environment, where the outer jacket of the O-ring is aluminum. Also, Al 6063-T5 is used in the TN systems to hold the radial neutron shield material, in which one side of the aluminum is embedded in borated polyester resin and the other side is in contact with steel.

3.2.3.1 General corrosion

General corrosion, also known as uniform corrosion, proceeds at approximately the same rate over a metal surface (Phull, 2003b). Freely exposed aluminum surfaces in contact with moist air or water are subject to general corrosion. The corrosion rate depends on solution composition, pH, and temperature. The corrosion rate of aluminum is normally controlled by the formation of a passive film of Al_2O_3 at the metal and water interface. The Pourbaix diagram for aluminum shows that aluminum is passive in the pH range of approximately 4 to 8.5 at 25 degrees C [77 degrees F] (Kaufman, 1999). However, the aluminum passive film is reported to be more porous than the chromium oxide film that passivates stainless steel materials (Bass, 1956).

Aluminum subcomponents exposed to helium

Above a temperature of about 230 degrees C [446 degrees F], an aluminum protective film no longer develops in the presence of water or steam (Ghali 2010; 2011). As such, general corrosion of aluminum is possible if exposed to moisture, because initial temperatures near the spent fuel are above 200 degrees C [392 degrees F]. However, there is very little residual water in the cask internal environment following drying. Assuming a residual water content of 1 liter (L) [0.26 gallon (gal)], Jung et al. (2013) calculated that oxidation of all aluminum in the basket assembly is limited to just 0.54 g [0.019 oz], which is equivalent to a 20- or 2-μm [0.79- or 0.079-mils]-thick layer of aluminum over a surface area of 100 or 1,000 cm^2 [15.5 or 155 in^2]. This suggests that material thinning from oxidation is a very small fraction of the millimeter-thick [tens of mils-thick] aluminum materials used inside the system. As a result, sufficient general corrosion to challenge SSC functions is not credible, and therefore, aging management is not required during the 60-year timeframe in helium environments.

Aluminum subcomponents exposed to sheltered and embedded (all) environments

Section 3.2.1.1 discussed how an aqueous electrolyte can be developed under a sheltered environment through deliquescence of deposited salts. The deliquescent brine can be concentrated and acidic, initiating general corrosion. Therefore, general corrosion of aluminum lid seals exposed to a sheltered environment is considered to be credible, and aging management is required during the 60-year timeframe.

Anodized aluminum, in which a surface oxide film is deliberately formed in an electrochemical process, can increase the resistance to corrosion (Vargel, 2004). The successful formation of a protective oxide during manufacture depends on the anodizing solution, applied voltages, and sealing operations. Because of its anodized film and the relatively low temperatures present, general corrosion of the NUHOMS aluminum heat shield is not considered to be credible. However, if defects develop in the anodized film, deep pitting in the underlying metal could occur, and this is discussed below in Section 3.2.3.2. In the embedded environment, because it is moisture free, general corrosion is also not considered to be credible. Therefore, aging management is not required during the 60-year timeframe for anodized aluminum exposed to a sheltered environment and standard aluminum exposed to embedded environments.

3.2.3.2 Pitting and crevice corrosion

As discussed in Section 3.2.1.2, pitting corrosion is a localized form of corrosion that is confined to a point or small area of a metal surface (Frankel, 2003), and crevice corrosion occurs in a wetted environment when a crevice exists that allows a corrosive environment to develop in a component (Kelly, 2003). Aluminum and its alloys form a passive film on the surface. Localized corrosion in the form of pitting or crevice corrosion could occur for these passive aluminum materials, especially in the presence of halides.

Aluminum subcomponents exposed to sheltered environments

Section 3.2.1.1 discussed how an aqueous electrolyte can be developed on a stainless steel canister surface in a sheltered environment through deliquescence of deposited salts. The aluminum heat shield would be expected to be cooler than the canister surface, because it is farther away from the fuel, and thus the time to reach the critical temperatures for the development of an aqueous electrolyte in sheltered environments is much lower.

The protection of aluminum against corrosion, especially the anodized material, depends on the stability of the passivating oxide films. In chloride-rich environments, the passive layer breaks down and pitting corrosion becomes the predominant corrosion mode (Foley, 1986; Nguyen and Foley, 1979). Analyses of surface deposits demonstrate that aluminum exposed to sheltered environments accumulates adherent particles containing large concentrations of chloride and sulfate ions (Munier, 1982). Pitting corrosion rates on the order of 25 μm/yr [0.98 mils/yr] have been reported in seawater (Summerson et al., 1957). In 1 molar NaCl solution, crevice corrosion rates of aluminum can be as large as 1.3 mm/yr [51 mils/yr] (Baumgattner and Kaesche, 1988).

Because temperatures of aluminum heat-shield surfaces are expected to drop below the deliquescence threshold for airborne salts during the 60-year timeframe, and the corrosion rate is not negligible, pitting and crevice corrosion of aluminum in sheltered environments is considered to be credible, and therefore, aging management is required.

Aluminum subcomponents exposed to helium and embedded environments

Pitting and crevice corrosion of aluminum is not considered to be credible in helium and embedded environments because of (i) the lack of moisture and halides in helium environments within the cask or canister and (ii) low moisture and oxygen in the embedded environment. Therefore, aging management of pitting and crevice corrosion is not required for aluminum exposed to helium and embedded environments during the 60-year timeframe.

3.2.3.3 Galvanic corrosion

As discussed in Section 3.2.1.3, galvanic corrosion occurs when two dissimilar metals or conductive materials are in physical contact in the presence of a conducting solution (Baboian, 2003; Hack, 1993). In DSSs, galvanic coupling exists between aluminum and steel, stainless steel, and nickel (where aluminum is less noble in each case). For example, the aluminum lid seal is in contact with stainless steel in the TN-32 and TN-68 systems and an aluminum plate is in contact with the stainless steel fuel compartment within the TN-32 bolted cask.

Aluminum subcomponents exposed to sheltered environments

Section 3.2.1.1 discussed how an aqueous electrolyte conducive to corrosion can be developed in sheltered environments through deliquescence of deposited salts. Caseres (2007) reported corrosion rates of aluminum coupled to carbon steel of about 0.2 mm/yr [8 mils/yr] in solutions containing chloride ions. The galvanic corrosion rate of aluminum coupling to stainless steel is expected to be larger, because the corrosion potential difference between stainless steel and aluminum is larger than carbon steel and aluminum. Because an aqueous electrolyte conducive to corrosion may be present and corrosion of aluminum is expected to be enhanced under galvanic coupling, loss of material due to galvanic corrosion of aluminum is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Aluminum subcomponents exposed to helium

There is very little residual water within a cask or canister following drying. Assuming a residual water content of 1 L [0.26 gal], Jung et al. (2013) calculated that oxidation of all aluminum in the basket assembly is limited to 0.54 g [0.019 oz], which is equivalent to a 20 or 2-μm [0.79- or 0.079-mils]-thick layer of aluminum over a surface area of 100 or 1,000 cm^2

[15.5 or 155 in^2]. This suggests that material thinning from oxidation is a very small fraction of the aluminum materials used inside the system. In conclusion, loss of material due to galvanic corrosion in helium environments is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.3.4 Microbiologically influenced corrosion

As discussed in Section 3.2.1.4, MIC is corrosion caused or promoted by the metabolic activity of microorganisms (Dexter, 2003). Microorganisms can live in many environments, such as water, soil, and air, where aerobic bacteria (e.g., iron-manganese oxidizing bacteria, sulfur/sulfide oxidizing bacteria, methane producers, organic acid-producing bacteria), fungi, and algae can develop.

Aluminum subcomponents exposed to sheltered environments

Section 3.2.1.1 discussed how an aqueous electrolyte conducive to corrosion can be developed in sheltered environments through deliquescence of deposits. This electrolyte also has the potential to support microbial activity.

A single research study found MIC on an aluminum compact disc exposed to tropical atmospheres (Garcia-Guinea et al., 2001). However, there is no operating experience of MIC degradation of aluminum engineering components that operate in environments similar to those of dry cask storage systems. All of the operating experience of MIC for metallic components is from conditions in which the metal surface is kept continuously wet. Due to the absence of any applicable experience of MIC damage of aluminum components under atmospheric conditions, MIC is not considered to be significant in sheltered environments, and therefore, aging management is not required during the 60-year timeframe.

Aluminum subcomponents exposed to helium and embedded (all) environments

Because of the limited amount of water and nutrients in the helium environments within casks and canisters, and because of the limited water in embedded environments, MIC of aluminum is not credible for the 60-year timeframe, and therefore, aging management is not required.

3.2.3.5 Creep

Section 3.2.1.6 explained that, as a general rule of thumb, thermal activation is insufficient to produce significant creep at temperatures below $0.4T_m$, where T_m is the melting point of the metal in Kelvin (Cadek, 1988). With melting points of 911 to 930 K [638 to 657 degrees C ; 1,180 to 1,215 degrees F], temperatures of at least 364 to 372 K [91 to 99 degrees C ; 196 to 210 degrees F]] are required to initiate significant creep in aluminum. These temperatures are consistent with Sindelar et al. (2011), which indicates that creep in aluminum is possible at temperatures greater than 100 degrees C [212 degrees F]. Microstructure also plays a significant role in a metal's resistance to creep. Hence, while this 100 degrees C [212 degrees F] minimum temperature for creep is representative for pure aluminum, creep in precipitation hardened aluminum alloys does not become significant until about 200 degrees C [392 degrees F] (Samuels, 1988). Additionally, at temperatures near these threshold values, high stresses are required to produce creep.

Aluminum subcomponents exposed to helium

The highest temperatures within the DSSs are at locations close to the fuel rods, where the environment is helium. The maximum expected temperature of fuel cladding has been estimated to be 400 degrees C [752 degrees F] at the beginning of storage (Jung et. al., 2013). This cladding temperature is expected to decrease to around 266 degrees C [510 degrees F] after 20 years and to approximately 127 degrees C [261 degrees F] after 60 years. These estimates depend on many factors, such as the initial heat load of the SNF. Because the fuel rods are the only heat source within the cask or canister, these temperatures provide upper temperature limits for all subcomponents. It is apparent from these temperatures that subcomponents within the cask or canister could be exposed to temperatures above the minimum creep temperatures for aluminum during at least the first 40 years.

Because the minimum creep temperature will be exceeded during a portion of the 60-year period, it is necessary to consider the load applied to the subcomponent to determine whether creep deformation will occur and whether the creep affects safety. Subcomponents that do not serve a structural function are not expected to be under loads other than their own weight, and in many instances, their weight is also supported by adjacent structures. Due to the minimal applied loads, creep of nonstructural subcomponents will not produce significant damage during the 60-year timeframe. Conversely, aluminum subcomponents that serve a structural function may experience loads that are high enough to produce sufficient creep deformation to affect the subcomponents' safety functions.

Aluminum subcomponents exposed to sheltered and embedded (all) environments

Aluminum subcomponents exposed to sheltered and embedded environments experience lower temperatures than those experienced by the internal subcomponents. Time-temperature profiles calculated for the canister surface (EPRI, 2006; Meyer et al., 2013) suggest that temperatures in excess of 200 degrees C [392 degrees F] could initially be present on portions of the canister surface and temperatures above 100 degrees C [212 degrees F] could persist for 30 years. Based on these temperatures, creep is credible during the 60-year timeframe but only on aluminum subcomponents that are attached directly to the canister shell or cask wall and have a structural function.

The NRC reviewer should review the creep analyses for aluminum structural components that are exposed to the elevated temperatures discussed above, as contained in the applicant's original design-bases documents, to determine whether the renewal application adequately addresses the implications of extending the operating period to 60 years. This reexamination of the original analyses would typically be defined as TLAAs in the renewal application. The staff's guidance for the review of TLAAs is provided in NUREG–1927, Revision 1. If the original design basis does not include the pertinent analyses, the reviewer nevertheless should ensure that the application addresses this potential aging mechanism.

If the TLAA or other supplemental analyses demonstrate that creep does not have the potential to challenge an important-to-safety function, aging management is not required during the 60-year timeframe.

Conversely, an applicant may conclude that an analysis cannot support a determination that creep damage will not challenge an important-to-safety function in the 60-year timeframe of the period of extended operation. In that case, the applicant may manage the aging of the associated SSC with an AMP.

3.2.3.6 Fatigue

As discussed previously in Section 3.2.1.7, because spent fuel storage is a static application, cyclic loading by a purely mechanical means is largely limited to transfer cask lifting trunnions. Some aluminum subcomponents, however, could experience cyclic loads due to thermal effects, such as those caused by daily and seasonal fluctuations in the temperature of the external environment.

The NRC reviewer should review the fatigue analyses contained in the applicant's original design-basis documents to determine whether the renewal application adequately addresses the implications of extending the operating period to 60 years. This reexamination of the original fatigue analyses would typically be defined as TLAAs.

As described in greater detail in Chapter 5 of this report, the reviewer should review the design codes and standards to identify any required fatigue analyses and ensure that the applicant addresses those analyses with a TLAA. For example, components that were designed in accordance with the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Section III, Division 1, Subsections NB or NC (ASME, 2007a) were evaluated for the effects of cyclic loading per subparagraphs NB 3222.4 and NC 3219.2, respectively.

The staff's guidance for the review of TLAAs is provided in NUREG–1927, Revision 1, and Chapter 5 of this report. In its evaluation of a TLAA, an applicant may conclude that an analysis can no longer support a determination that aging will not adversely affect an important-to-safety function in the 60-year timeframe of the period of extended operation. In that case, the applicant may manage the aging of the associated SCC with an AMP.

The AMR tables in Chapter 4 recommend that applicants address any applicable TLAAs associated with components with a structural function. If no fatigue analysis was performed in support of the component design, no action is required of the applicant.

3.2.3.7 Thermal aging

The microstructures of many aluminum alloys will change, given sufficient time at temperature. This process is commonly called thermal aging. The effect of the thermal aging on mechanical properties will depend on the time at temperature and the microstructure and chemical composition of the aluminum components. In some DSSs, Al 1100 and its 6000 series alloys are used inside and outside the system to transfer heat because of their good thermal conductivity.

Aluminum subcomponents exposed to helium, sheltered, and embedded (all) environments

The 6000 series aluminum alloys, such as 6061 and 6063 used in the system internals, are precipitation-hardened alloys. The precipitation treatment is performed between 163 and 204 degrees C [325 and 399 degrees F] (ASM International, 1991). Prolonged elevated temperature exposure is known to significantly reduce the strength of these alloys due to microstructural changes. For example, Farrell (1995) shows that, when alloy 6061-T6 is held at 200 degrees C (392 degrees F), its yield strength drops from approximately 18 ksi at 10,000 hours (1.14 years) to approximately 11.5 ksi at 100,000 hours (11.4 years). Because of this sensitivity to exposure time, ASME B&PV Code Section II requires that time-dependent properties be used for exposures above 177 degrees C (350 degrees F) for this alloy.

The maximum expected temperature of fuel cladding has been estimated to be 400 degrees C [752 degrees F] at the beginning of storage (Jung et. al., 2013). This cladding temperature is expected to decrease to around 266 degrees C [510 degrees F] after 20 years and to approximately 127 degrees C [261 degrees F] after 60 years. It is apparent from these temperatures that the 6061 and 6063 aluminum alloys may experience significant overaging at a higher temperature than that for precipitation treatment, leading to loss of strength. This loss of strength could be an issue for any subcomponents that perform a structural function. Because Al 1100 aluminum is not a precipitation-hardened alloy, it will not experience any overaging. However, if it is used in the cold worked state, it will anneal at temperatures above 300 degrees C [572 degrees F] (ASM International, 1991). This annealing will reduce strength, which could be significant for subcomponents that serve a structural function.

Aluminum subcomponents exposed to sheltered and embedded environments experience lower temperatures than the internal subcomponents. Time-temperature profiles calculated for the canister surface (EPRI, 2006; Meyer et al., 2013) suggest that temperatures in excess of 200 degrees C [392 degrees F] could initially be present on portions of the canister surface and temperatures above 100 degrees C [212 degrees F] could persist for 30 years. Based on these temperatures, thermal aging could occur on aluminum subcomponents that have a structural function and are attached directly to the canister shell or cask wall.

Because thermal aging of aluminum is a possible aging mechanism, the NRC reviewer should review any aging analyses for aluminum structural components that are exposed to the elevated temperatures discussed above, as contained in the applicant’s original design-bases documents, to determine whether the renewal application adequately addresses the implications of extending the operating period to 60 years. This reexamination of the original analyses would typically be defined as TLAAs in the renewal application. The staff’s guidance for the review of TLAAs is provided in NUREG–1927, Revision 1. If the original design basis does not include the pertinent analyses, the reviewer nevertheless should ensure that the application addresses the potential for thermal aging to adversely affect the structural function of aluminum components.

3.2.3.8 Radiation embrittlement

Embrittlement of metals may occur under exposure to neutron radiation. Depending on the neutron fluence, radiation can cause changes in mechanical properties, such as loss of ductility, fracture toughness, and resistance to cracking.

Farrell and King (1973) showed that pure aluminum had increased strength but decreased ductility after being irradiated to fast fluences in the range of 1 to 3 × 10^{22} n/cm^2 [6.5 to 19.4 × 10^{22} n/in^2] from a research reactor for 8 years. Alexander (1999) showed that irradiation at 10^{22} n/cm^2 [6.5 × 10^{22} n/in^2] simulating reactor conditions affected the mechanical properties of aluminum alloy 6061-T651.

Some results from radiation testing of aluminum-based neutron poisons are reported in the literature (EPRI, 2009a). Gamma, thermal neutron, and fast neutron radiation testing of an aluminum-based laminate composite in water for 9 years and exposed to up to 7 × 10^{11} rad gamma, 3.6 × 10^{18} n/cm^2 [2.2 × 10^{19} n/in^2] fast neutron fluence, and 2.7 × 10^{19} n/cm^2 [1.7 × 10^{20} n/in^2] thermal neutron fluence showed no change in ultimate strength and no other signs of physical deterioration except for severe oxidation because of the presence of water. Also, radiation testing of an aluminum-based, sintered composite subjected to up to 1.5 × 10^{20} n/cm^2 [9.7 × 10^{20} n/in^2] fast neutron fluence and a maximum of 3.8 × 10^{11} rad gamma exposure showed little change in the yield strength and ultimate strength (EPRI, 2009a). Finally, neutron radiation of borated aluminum to fluences of 10^{17} n/cm^2 [6.5×10^{17} n/in^2] showed no dimensional change or radiation damage (EPRI, 2009a). These test conditions are expected to be more severe than those experienced by aluminum alloys in the extended storage application (EPRI, 2009a).

As discussed in Section 3.2.1.9 of this report, the maximum potential accumulated neutron fluence on DSS components after 100 years was calculated to be 2.63×10^{16} n/cm^2 [1.70×10^{17} n/in^2]. This fluence is well below the levels that have been found degrade the mechanical properties of aluminum alloys. Thus, radiation embrittlement of aluminum subcomponents exposed to any environment is expected to be insignificant, and therefore, aging management is not required during the 60-year timeframe.

3.2.4 Nickel alloys

Nickel alloys are used in only a few DSS applications. In the HI-STAR overpack, nickel alloy 718 (ASME SB637) is used to construct closure plate bolts and trunnion bolts, and nickel alloy X750 is used to construct seals. These components are exposed to an outdoor environment. Nickel alloy 718 (ASME SB637) is also used to construct the trunnion for the HI-TRAC transfer cask, which is predominantly exposed to an indoor environment or otherwise encased without direct air ingress except for short periods of air exposure during transfer operations. For such air-indoor/outdoor environments, the aging effects from aqueous corrosion processes are expected to be bounded by those from the outdoor environment. Both nickel alloys 718 and X750 are precipitation-hardened alloys that contain chromium to form a passive oxide film on the surface (Crook, 2005).

3.2.4.1 General corrosion

The high chromium contents of alloys 718 and X750 (greater than 17 and 14 weight percent, respectively), make these alloys very resistant to general corrosion, even in such reducing acids as hydrochloric acid (Crook, 2005). Because of its passive behavior and high corrosion resistance, general corrosion of nickel alloys exposed to outdoor environments is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.4.2 Pitting and crevice corrosion

As discussed in Section 3.2.1.2, pitting corrosion is a localized form of corrosion that is confined to a point or small area of a metal surface (Frankel, 2003) and crevice corrosion occurs in a wetted environment when a crevice exists that allows a corrosive environment to develop in a component (Kelly, 2003).

Section 3.2.1.1 discussed how an aqueous electrolyte can be developed in outdoor air. This electrolyte could contain chemical species such as halides and sulfides. Localized corrosion in the form of pitting and/or crevice corrosion may occur for some passive nickel alloys, but overall, nickel alloys are more resistant to localized corrosion than stainless steels (Crook, 2005). Nickel alloy 718 is used in sea water applications, where the chloride concentration is much higher than that from outdoor air. Furthermore, for many nickel alloys in different environmental systems, localized corrosion growth is often observed to slow down or stop, which is referred to as the stifling and arrest phenomena (He and Dunn, 2007). Because of the high corrosion resistance, pitting or crevice corrosion of nickel subcomponents exposed to outdoor air is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.4.3 Microbiologically influenced corrosion

As discussed in Section 3.2.1.4, MIC is corrosion caused or promoted by the metabolic activity of microorganisms (Dexter, 2003). Microorganisms can live in many environments, such as water, soil, and air, where aerobic bacteria (e.g., iron-manganese oxidizing bacteria, sulfur/sulfide oxidizing bacteria, methane producers, organic acid-producing bacteria), fungi, and algae can develop.

Although the moisture necessary to support microbial activity may be present on surfaces exposed to outdoor environments, all of the operating experience of MIC of metallic components is from conditions where the surface is continuously wet. Furthermore, there is no operational or experimental evidence of MIC degradation of nickel-chromium alloys similar to 718 and X750 (Little and Lee, 2009). Due to the absence of any operating experience of MIC damage to nickel alloys under atmospheric conditions, MIC of nickel subcomponents exposed to outdoor air is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.4.4 Stress corrosion cracking

As discussed in Section 3.2.1.5, SCC is the cracking of a metal produced by the combined action of corrosion and tensile stress (applied or residual) (Jones, 1992, 2003). SCC of nickel alloys has been experienced in high-temperature water and hot caustic solutions (Phull, 2003). These conditions do not exist in the outdoor air environment of DSSs. Although chloride-containing electrolytes could develop in outdoor air, as discussed in Section 3.2.1.1, nickel-based alloys are known to be highly resistant to the chloride-induced SCC that affects stainless steels. In indoor air, the probability of developing a corrosive aqueous electrolyte is negligible. Because alloys 718 and X750 are not susceptible to the dry storage outdoor air environments, SCC is not expected to be credible. Therefore, aging management is not required during the
60-year timeframe.

3.2.4.5 Fatigue

As discussed previously in Section 3.2.1.7, because spent fuel storage is a static application, cyclic loading by a purely mechanical means is largely limited to transfer cask lifting trunnions, which are loaded each time a canister is moved from the spent fuel pool to the dry storage pad. Other subcomponents, however, could experience cyclic loads due to thermal effects, such as those caused by daily and seasonal fluctuations in the temperature of the external environment.The NRC reviewer should review the fatigue analyses contained in the applicant's original design-basis documents to determine whether the renewal application adequately addresses the implications of extending the operating period to 60 years. This reexamination of the original fatigue analyses would typically be defined as TLAAs.

In some cases, fatigue analyses may have been performed to support the original design but are not explicitly discussed in the design basis documentation. As a result, the reviewer should review the design codes and standards to identify any required fatigue analyses and ensure that the applicant addresses those analyses with a TLAA. For example, components that were designed in accordance with the American Society of Mechanical Engineers Boiler and

Pressure Vessel Code (ASME Code) Section III, Division 1, Subsections NB or NC (ASME, 2007a) were evaluated for the effects of cyclic loading per subparagraphs NB 3222.4 and NC 3219.2, respectively.

The staff's guidance for the review of TLAAs is provided in NUREG–1927, Revision 1, and summarized in Chapter 5 of this report. In its evaluation of a TLAA, an applicant may conclude that an analysis can no longer support a determination that aging will not adversely affect an important-to-safety function in the 60-year timeframe of the period of extended operation. In that case, the applicant may manage the aging of the associated SCC with an AMP.

The AMR tables in Chapter 4 recommend that applicants address any applicable TLAAs associated with components with a structural function. If no fatigue analysis was performed in support of the component design, no action is required of the applicant.

3.2.4.6 Radiation embrittlement

Depending on the neutron fluence, radiation can cause changes in mechanical properties such as loss of ductility, fracture toughness, and resistance to cracking. Nickel-based alloys experienced significant reductions in tensile ductility during neutron irradiation at elevated temperatures of 400–600 degrees C [752–1,112 degrees F] for neutron doses approaching 10–15 displacements per atom (dpa), which corresponds to a neutron fluence of about 10^{21}–10^{22} n/cm^2 [6.5 × 10^{21}–6.5 × 10^{22} n/in^2] (Was et al., 2006; Rowcliffe, 2009). Nickel alloy X-750 cracking has been observed extensively in nuclear power plant applications after attaining an end-of-life fluence of 1 to 10 × 10^{21} n/cm^2 [6.5 to 65 × 10^{21} n/in^2] (Was et al., 2006).

As discussed in Section 3.2.1.9 of this report, the maximum potential accumulated neutron fluence on DSS basket components after 100 years was calculated to be 2.63 × 10^{16} n/cm^2 [1.70 × 10^{17} n/in^2]. This fluence is five to six orders of magnitude below the level at which the mechanical properties of nickel have been observed to be degraded. In addition, for the nickel overpack and transfer cask subcomponents, the neutron exposure is significantly lower than the calculated exposure for the basket components in Section 3.2.1.9. Thus, radiation embrittlement of nickel alloys is expected to be insignificant, and therefore, aging management is not required during the 60-year timeframe.

3.2.4.7 Stress relaxation

Section 3.2.1.10 explained that stress relaxation of bolting is the steady loss of stress due to atomic movement at elevated temperature in a loaded part where dimensions are fixed (Earthman, 2000). The service temperature limit for nickel alloy 718 is 649 degrees C [1,200 degrees F] (Bickford, 2008), which is much higher than the external temperature of the HI-STAR overpack in which nickel bolts are used. Below the service temperature limit, the bolts are expected to maintain their original clamping force. Thus, stress relaxation of nickel alloy subcomponents exposed to the outdoor environment is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.4.8 Wear

Fretting wear is the repeated cyclical rubbing between two surfaces. For the HI-TRAC transfer cask exposed to air-indoor/outdoor environments, the nickel alloy used to construct the lifting trunnion may experience cyclic rubbing during loading and unloading. Thus, wear of the nickel alloy is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

3.2.5 Copper alloys

Copper alloys are used in only a few DSS applications. In the HI-STAR overpack, brass, which is a copper-zinc alloy containing more than 50 percent copper, is used as the rupture disk material. In the NUHOMS HSM, copper is used to construct the lightning protection system. Both subcomponents are exposed to outdoor air.

3.2.5.1 General corrosion

General corrosion, also known as uniform corrosion, proceeds at approximately the same rate over a metal surface (Phull, 2003b). Freely exposed copper surfaces in contact with moist air or water are subject to general corrosion. The corrosion rate depends on solution composition, pH, and temperature. The copper Pourbaix diagram (Pourbaix, 1974) indicates that copper and copper alloys are reactive with water in the presence of oxygen, but the low corrosion rate has allowed their wide use in industrial, marine, and rural atmospheres (Cohen, 2005). General corrosion of copper and its alloys is the predominant corrosion mode, because they do not form a truly passive oxide film on the surface.

Atmospheric corrosion of copper has been observed and studied extensively (Leidheiser, 1974; Rozenfeld, 1972). The corrosion rate of copper is strongly dependent on relative humidity and the concentration of pollutants in the air (e.g., chlorides, sulfur dioxide, hydrogen sulfide). The presence of NaCl in a marine environment has a strong corrosive effect toward copper under thin electrolyte layers and in alternating wet and dry cyclic conditions. Copper corrosion rates usually decrease with time, following an exponential decay law (Feliu et al., 1993). Typical corrosion rates of copper exposed to marine and industrial environments are 0.6–2.5 μm/yr [0.024–0.098 mils/yr] and 1.3 μm/yr [0.051 mils/yr], respectively (Tracy, 1955; Herman and Castillo, 1974). Fonseca et al. (2004) recorded copper corrosion in marine environments as high as 7.8 μm/yr [0.31 mils/yr]. In atmospheric marine environments, copper corrosion is on the order of 16 μm/yr [0.62 mils/yr] (Farro et al., 2009). Assuming a corrosion rate of 10 μm/yr [0.39 mils/yr], the metal loss could be 0.6 mm [23.6 mils] over 60 years. As such, general corrosion of copper alloys exposed to an outdoor air environment is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

3.2.5.2 Pitting and crevice corrosion

As discussed in Section 3.2.1.2, pitting corrosion is a localized form of corrosion that is confined to a point or small area of a metal surface (Frankel, 2003), and crevice corrosion occurs in a wetted environment when a crevice exists that allows a corrosive environment to develop in a component (Kelly, 2003).

The common form of atmospheric corrosion for copper exposed to outdoor air is general corrosion, because copper alloys do not have a true protective film (Cohen, 2005). In an oxidizing environment, copper could experience surface roughening, initially appearing like localized corrosion; however, localized corrosion tends to converge with general corrosion (i.e., the penetration front of localized corrosion merges with that of general corrosion). Long-term tests of copper alloys show that the average pit depth does not continually increase with extended times of exposure (Cohen, 2005). Copper has been commonly used for architectural components exposed to outdoor air for many years, such as when used for roofing, building fronts, and statues, where localized corrosion is not shown to be evident. Because localized corrosion is not a primary corrosion mechanism for copper alloys exposed to outdoor air, and it tends to converge with general corrosion, it is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.2.5.3 Microbiologically influenced corrosion

As discussed in Section 3.2.1.4, MIC is corrosion caused or promoted by the metabolic activity of microorganisms (Dexter, 2003). Although the moisture necessary to support microbial activity may be present on surfaces exposed to the outdoor environment, all of the operating experience of MIC of metallic materials is from conditions under which the surface is continuously wet, and it is unclear whether these rates could be sustained if the conditions to support MIC are only present on an intermittent basis. Furthermore, there is no experimental evidence of MIC degradation of copper alloys under atmospheric conditions. Due to the absence of any operating experience of MIC damage of copper alloys under atmospheric conditions, MIC is not considered to be significant, and therefore, aging management is not required during the 60-year timeframe.

3.2.5.4 Radiation embrittlement

Depending on the neutron fluence, radiation can cause changes in mechanical properties, such as loss of ductility, fracture toughness, and resistance to cracking. Radiation hardening and embrittlement of pure copper and copper-based alloys have been observed at temperatures in the range of 60–90 degrees C [140–194 degrees F] in the dose range of 10^{-3}–10^{-1} dpa (Fabritsiev et al., 2004). Blewitt et al. (1957) observed yield drop on stress–strain curves, hardening, and a decrease in uniform and total elongation upon irradiation of pure copper at 60 degrees C [140 degrees F] to doses of 10^{19} n/cm^2 [6.5 ×10^{19} n/in^2].

As discussed in Section 3.2.1.9 of this report, the maximum potential accumulated neutron fluence on DSS basket components after 100 years was calculated to be 2.63×10^{16} n/cm^2 [1.70×10^{17} n/in^2]. This fluence is at least three orders of magnitude below the level at which the mechanical properties of copper alloys have been reported to be degraded. In addition, for locations outside of the overpack where copper alloys are used, the accumulated dose is much lower than the level calcluated in Section 3.2.1.9. Thus, radiation embrittlement of copper alloys exposed to outdoor air is expected to be insignificant, and therefore, aging management is not required during the 60-year timeframe.

3.2.6 Lead

Lead is used as gamma radiation shielding in the NUHOMS and Holtec transfer casks, as well as some NUHOMS dry shielded canister designs. In each case, the lead is encased in steel or stainless steel and thus is not exposed to water or atmospheric contaminants. Lead is well known to be very resistant to corrosion in a variety of environments (Alhasan, 2005). Because there are no credible aging mechanisms that could challenge the ability of lead to perform its shielding (and, in some cases, heat transfer) functions, aging management of this material is not required during the 60-year timeframe.

3.2.7 Depleted uranium

Depleted uranium is used as a shield plug in the FuelSolutions canister. The material is encased in steel or stainless steel and thus is not exposed to water or atmospheric contaminants. Uranium is known to be resistant to corrosion in a variety of environments (Lillard and Hanrahan, 2005). Because there are no credible aging mechanisms that could challenge the ability of depleted uranium to perform its shielding functions, aging management of this material is not required during the 60-year timeframe.

3.2.8 Coatings

Coatings in DSSs are used primarily for corrosion mitigation, to facilitate decontamination, and to improve heat-rejection capability by increasing the emissivity of cask internal components. A wide array of coating materials is used to fulfill these functions, such as organic epoxy, inorganic zinc-rich coatings, galvanized zinc, aluminum, nickel, and cadmium. However, coatings are often present for operational purposes and may not be credited as supporting an important-to-safety function. Thus, the reviewer should examine the DSS design-basis documentation to verify that the renewal applicant appropriately identified the coatings that meet the renewal scoping criteria in NUREG–1927, Revision 1.

Coatings are exposed to outdoor air, indoor/outdoor air (transfer cask), and sheltered environments, which are characterized by elevated temperature and radiation exposure. As discussed in greater detail for neutron shielding materials in Section 3.3.1, polymeric materials may be susceptible to heat- and radiation-induced molecular scission (breaking) and cross-linking that can cause embrittlement and cracking.

The variety of coatings and the proprietary nature of many coating systems make a generic evaluation of specific degradation mechanisms impractical. Nevertheless, the NRC recognizes that coatings may degrade, either through aging or inappropriate application methods, and recommends in-service condition assessments of coatings to ensure that they continue to support their important-to-safety functions. NRC Regulatory Guide 1.54, Revision 2, “Service Level I, II, and III Protective Coatings Applied to Nuclear Power Plants,” references American Society for Testing and Materials (ASTM) standards that are considered appropriate guidance for coating maintenance in nuclear power plants (NRC, 2010d). The ASTM standards typically recommend periodic visual inspections for blistering, cracking, flaking/peeling, and rusting, which may be followed by physical tests when degradation is identified. Regulatory Guide 1.54 also notes that the Electric Power Research Institute (EPRI) Report 1019157, “Guideline on Nuclear Safety-Related Coatings,” Revision 2, provides additional information on the maintenance of coatings (EPRI, 2009b).

The reviewer should verify that the renewal applicant has an existing coating maintenance program or proposes a new aging management program for coatings that are credited with performing an important-to-safety function or protecting an important-to-safety component. The AMR tables identify thermal and radiation effects as most likely to degrade coatings, and a site-specific AMP consistent with ASTM guidelines is recommended to manage aging.

3.2.9 References

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3.3 Neutron shielding materials

Neutron shielding typically is provided by either borated or nonborated polymeric or cementitious materials. Hydrogen and oxygen reduce the energy of the neutrons such that the neutrons are more effectively absorbed by the boron. The degradation and possible relocation of shielding materials may be mitigated by encasing or reinforcing materials. For example, shielding is often cast within a metal liner, which prevents ingress of water and contaminants. Also, some shielding materials include reinforcements (e.g., fiberglass) for stability.

A set of known aging mechanisms with the potential to affect the performance of shielding materials was identified from reviews of a range of information; sources of the information include gap assessments for DSSs, relevant technical literature, and operating experience from nuclear applications (NRC, 2014a, 2010; Chopra et al., 2014; Hanson et al., 2012; Sindelar et al., 2011; NWTRB, 2010; EPRI, 2011). These mechanisms, which are induced by thermal and irradiation conditions, include boron depletion, thermal aging, and radiation embrittlement. Detailed discussions regarding each of these aging mechanisms follow.

3.3.1 Neutron-shielding materials

Polymer based

The TN-32 and TN-68 systems use both a borated polyester resin and polypropylene for shielding, while Holtec's HI-STAR overpack and HI-TRAC transfer cask use Holtite-A.^{TM} Holtite-A^{TM} is a composite material consisting of an epoxy polymer, boron carbide powder, and aluminum hydroxide.

Cement based

The cementitious BISCO NS-3 material is used in one of the NUHOMS transfer cask designs for neutron shielding. The structural concrete used to construct overpacks also serves as neutron and gamma shielding; the degradation of such concrete is discussed separately in Section 3.5.

3.3.1.1 Boron depletion (borated materials)

The boron concentration in the neutron shields decreases as boron atoms in the borated materials absorb neutrons. Boron-10 nuclei capture neutrons, yielding excited Boron-11 nuclei, which in turn decay into high-energy alpha particles and Lithium-7 nuclei. The neutron shielding material will lose one boron-10 atom per such a reaction. Significant depletion of boron-10 atoms may occur over time, if the shielding material is exposed to sufficient neutron fluence.

The NRC reviewer should ensure that the applicant provides a bounding analysis to show that boron-10 depletion is not a credible aging mechanism for its specific DSS design. The reviewer should review any boron depletion analyses contained in the applicant's original design-bases documents, if present, to determine whether the design-basis analysis or license renewal application adequately addresses the implications of extending the operating period to 60 years. This reexamination of the original analyses would typically be defined as TLAAs in the renewal application. The staff's guidance for the review of TLAAs is provided in NUREG–1927, Revision 1 (NRC, 2016). If the original design basis does not include an analysis for loss of boron-10, the reviewer nevertheless should ensure that the renewal application adequately addresses this aging mechanism.

Rather than demonstrating performance through an analysis, an applicant may choose to manage loss of neutron shielding, such as through radiation monitoring, to confirm the shielding's continued effectiveness. In that case, the reviewer should refer to NRC guidance on the review of AMPs in NUREG–1927, Revision 1.

3.3.1.2 Thermal aging

Polymers may be susceptible to heat-induced changes to material properties and configuration due to a number of mechanisms. At elevated temperatures, the long chain backbone of a polymer can undergo molecular scission (breaking) and cross linking. Also, gaseous products may be formed, including H_2, CH_4, and CO_2. These reactions may cause embrittlement, shrinkage, decomposition, and changes in physical configuration (e.g., loss of hydrogen or water) (EPRI, 2002; McManus and Chamis, 1996). Shrinkage and embrittlement can locally displace shielding material and potentially diminish shielding effectiveness, although this may be mitigated in part by reinforcement materials within the polymer matrix and the support provided by the encasing metal. Because many polymers are known to degrade at elevated temperatures, thermal aging for polymer-based neutron-shielding materials is a credible aging mechanism. Therefore, either a supporting analysis for the material's continued use or an AMP is required during the 60-year timeframe.

The cementitious BISCO NS-3 shielding material used in one of the NUHOMS transfer cask designs may experience some loss of hydrogen (neutron moderator) when exposed to elevated temperatures. However, the material is subjected to elevated temperatures only during relatively brief periods when the storage canister is being transported from the spent fuel pool to the storage pad. Thus, the time of thermal exposure in the transfer cask is minimal compared to the continuous thermal exposure NS-3 experiences in other NRC-approved applications (e.g., the MC-10 metal storage cask) (NRC, 2005). As a result, thermal aging of the NS-3 shielding material is not considered to be a credible aging mechanism in the transfer cask, and therefore, aging management is not required during the 60-year timeframe.

3.3.1.3 Radiation embrittlement

Similar to the thermal aging mechanism discussed above, radiation can alter polymer structures by molecular scission and cross linking to reduce ductility, fracture toughness, and resistance to cracking (Fu, et al., 1988; Cota, et al., 2007). For example, the threshold for radiation embrittlement has been found to be about 10^6 rad for polyethylene and significantly lower for other polymers, such as polytetrafluoroethylene (EPRI, 1998). Depending on the DSS design and the specific SNF, this dose can be reached in 10–100 years (EPRI, 1998). Embrittlement can locally displace shielding material and potentially reduce shielding effectiveness, although this may be mitigated, in part, by reinforcement materials within the polymer matrix and the support provided by the encasing metal. As a result, radiation embrittlement of polymer-based neutron-shielding materials is a credible aging mechanism, and therefore, either a supporting analysis for the material's continued use or an AMP is required during the 60-year timeframe. An acceptable AMP may include monitoring and trending of radiation dose to confirm the absence of an decreasing trend in shielding effectiveness.

An analysis of the effects of radiation on the shielding properties of BISCO NS-3 has shown that both the gamma and neutron radiation dose the shielding material receives over 60 years in the NUHOMS transfer cask are several orders of magnitude below the material's exposure limit (BISCO, 1986; NRC, 2014b). As a result, radiation embrittlement of the NS-3 shielding material is not considered to be a credible aging mechanism, and therefore, aging management is not required during the 60-year timeframe.

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3.4 Neutron poison materials

Subcriticality of the SNF in DSSs may be maintained, in part, by the placement of neutron absorbers, or poison plates, around the fuel assemblies. Commonly used neutron poisons include borated stainless steel, borated aluminum alloys, aluminum metal-matrix composites such as Metamic™ and Boralyn®, and aluminum-boron carbide laminate composites, commonly referred to as cermets, such as Boral®. These materials are exposed to helium environments, where temperature and radiation levels are expected to be high because of their proximity to the fuel assemblies. This environment also could include small amounts of water left after the drying operations.

A list of known aging mechanisms that have the potential to affect the performance of neutron poison plates was identified from reviews of a range of information sources, including gap assessments for DSSs, relevant technical literature, and operating experience from nuclear and nonnuclear applications (NRC, 2014, 2010; Chopra et al., 2014; Hanson et al., 2012; Sindelar et al., 2011; NWTRB, 2010). These mechanisms, which are induced by various physicochemical, thermal-mechanical, and irradiation conditions, include general corrosion, galvanic corrosion, wet corrosion and blistering, creep, thermal aging, radiation embrittlement, and boron depletion.

3.4.1 Borated stainless steel

The Type 304 borated stainless steels used as neutron poison plates are similar in composition to standard Type 304 stainless steels used in other engineering applications, except that the borated steels contain boron, which has a much higher thermal neutron absorption cross section. ASTM A887–89 defines eight types of borated stainless steels (304B and 304B1–304B7) with natural boron concentrations (including both B-10 and B-11 isotopes) ranging from 0.2 to 2.25 weight percent (ASTM International, 2009). Boron is essentially insoluble in stainless steel, and thus it is present as iron and chromium borides (Fe_2B, Cr_2B) in a steel matrix.

Of the identified aging mechanisms for neutron poison plates discussed in Section 3.4 above, the following were removed from consideration for aging effects of borated stainless steels, because they were determined not to be reasonably credible: (i) general corrosion, (ii) galvanic corrosion and (iii) wet corrosion and blistering. The technical justifications for the decisions to eliminate these aging mechanisms follow.

- *General corrosion:* Similar to other austenitic stainless steel alloys, borated stainless steel exhibits passive behavior in helium environments, and thus, general corrosion rates are expected to be negligible.

- *Galvanic corrosion:* Borated stainless steel could be coupled to steel, aluminum, or other stainless steel alloys. The galvanic corrosion behavior of stainless steel is complicated by the fact that its relative nobility with respect to other materials may depend on whether a passivating oxide film is present. Nevertheless, both passivated and nonpassivated stainless steels are generally more noble than steel and aluminum (Baboian, 2003). In addition, there is no aqueous electrolyte inside the cask or canister to support galvanic corrosion in the helium environment.

- *Wet corrosion and blistering:* Because borated stainless steel is solid without porosity, no water can be trapped inside the material. Thus, wet corrosion and blistering are not considered to be credible.

More detailed discussions regarding the other aforementioned potential aging mechanisms for borated stainless steel are provided below.

3.4.1.1 Boron depletion

Boron depletion in boron-based neutron poison plates refers to the loss of boron and hence the loss of the neutron-absorbing capacity of a material when it is exposed to neutron fluence. For example, under a neutron fluence, boron-10 nuclei capture neutrons, yielding excited Boron-11 nuclei, which in turn decay into alpha particles and Lithium-7 nuclei. In this nuclear reaction, one neutron absorption reaction results in the loss of one boron-10 atom. Significant depletion of boron-10 atoms may occur if the poison material is exposed to sufficient neutron fluence.

Borated stainless steel typically has an areal density of 10^{19} to 10^{21} boron-10 atoms/cm^2 [6.5×10^{19} to 10^{21} boron-10 atoms/in^2] (EPRI, 2009). The boron areal density can reach this level by adjusting the thickness of the poison plate, by adjusting the weight fraction of added boron, and through the use of enriched boron (i.e., boron-10) (EPRI, 2009). A neutron flux of 10^4–10^6 n/cm^2-s [6.5×10^4–6.5×10^6 n/in^2-s] is typical for dry cask storage (Sindelar et al., 2011). At a typical neutron flux and boron-10 concentration, the neutron poison plates would deplete at most 0.0002 percent of the available boron-10 atoms after 60 years of storage. Using the highest expected neutron flux and the lowest boron-10 concentration as a most conservative scenario, only 0.02 percent of the available boron-10 atoms would be depleted after 60 years, an amount too small to decrease the criticality control function of the neutron-absorbing materials. As such, boron depletion is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Although boron depletion in borated stainless steel is not generally considered to be a credible aging mechanism, the reviewer nevertheless should ensure that the renewal application addresses any depletion analyses that exist in the orginal design basis to consider the implication of extending the operating period to 60 years. Staff guidance for the review of such TLAAs is provided in NUREG–1927.

3.4.1.2 Creep

As discussed in Section 3.2.1.6, as a general rule of thumb, significant creep can occur at temperatures above $0.4T_m$, where T_m is the melting point of the metal in Kelvin (Cadek, 1988). At these temperatures, plastic deformation or distortion can occur over long times, even under stresses that normally would not be considered sufficient to cause yielding of the material. Robino and Cieslak (1997) show that borated stainless steel has a melting range of 1,250–1,340 degrees C [2,282–2,444 degrees F], corresponding to the melting of borides and the austenitic structure, which is slightly lower than standard nonborated stainless steel. Applying the $0.4T_m$ rule, a temperature range of 336–372 degrees C [637–702 degrees F] is required to initiate significant creep in borated stainless steels, which is below the estimated peak fuel cladding temperature of 400 degrees C [752 degrees F] at the beginning of the storage period (Jung et al, 2013). The maximum cladding temperature is estimated to drop below the creep range (336 degrees C [637 degrees F]) in fewer than 9 years, well before the period of extended operation. Also, the borated stainless steel poison plates, which are used in the verticle DSSs, are not expected to be under loads other than their own weight, and in many instances, their weight is also supported by adjacent structures. As such, creep of borated stainless steel is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.4.1.3 Thermal aging

As previously discussed in Section 3.2.2.8, the microstructures of most stainless steels will change, given sufficient time at elevated temperatures, and this can affect its mechanical properties. The thermal aging resistance highly depends on material chemical composition and microstructure. Borated stainless steel alloys consist of $(Fe,Cr)_2B$ precipitates dispersed in an austenite stainless steel matrix. Robino and Cieslak (1997) showed that the estimated peak fuel cladding temperature of 400 degrees C [752 degrees F] in storage (Jung et al, 2013) is well below the temperatures that are needed to cause a change in the boride precipitates. Also, as discussed in Section 3.2.2.8, the austenite matrix is not expected to be susceptible to microstructure changes until temperatures exceed 1,000 degrees C [1,832 degrees F]. As such, thermal aging of borated stainless steel is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.4.1.4 Radiation embrittlement

Embrittlement of metals occurs when radiation displaces atoms in metal crystal structures, creating defects. Neutron radiation (rather than gamma radiation) has the greatest potential to cause this phenomenon. Depending on the neutron fluence, radiation can cause changes in mechanical properties such as loss of ductility, fracture toughness, and resistance to cracking.

Neutron embrittlement effects on the mechanical properties and the microstructures of borated stainless steel were studied by irradiating borated stainless steel to different radiation levels, from 10^{13} to 10^{17} n/cm^2 [6.5×10^{13} to 10^{17} n/in^2] (Soliman et al., 1991). Tests included samples manufactured by both powder metallurgical and conventional wrought processes. The energy of the neutron source was such that approximately 20 percent of the neutron flux had an energy above 0.1 megaelectron-volt (MeV), meaning that a significant portion of the flux contained the most damaging intermediate or fast neutrons. The investigators reported that there was almost no change in mechanical properties with the fluence level up to 10^{17} n/cm^2 [6.5×10^{17} n/in^2]. As discussed in Section 3.2.1.9, for dry cask storage, the maximum potential accumulated neutron fluence on DSS basket components after 100 years was calculated to be 2.63×10^{16} n/cm^2 [1.70×10^{17} n/in^2], which is about one order of magnitude below the level of that used in the tests by Soliman et al. (1991). In addition, neutron flux decreases with time during storage, which will limit the radiation effects. As such, radiation embrittlement of borated stainless steel is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.4.2 Borated aluminum alloys and aluminum-based composites

As in stainless steels, boron is essentially insoluble in aluminum. In borated aluminum, boron is present in the form of aluminum or titanium boride precipitates (AlB_2, TiB_2) that reside in an aluminum matrix. In aluminum metal-matrix composites, boron is in the form of boron carbides (B_4C) in an aluminum matrix. The laminate composites (e.g., Boral®) consist of (i) a core of uniformly distributed boron carbide and aluminum alloy particles and (ii) a surface cladding of aluminum alloy on both sides of the core.

Of the identified potential aging mechanisms for neutron poison plates listed in Section 3.4 above, wet corrosion and blistering are considered to be credible only for Boral®, because only this material has porosity that can trap water and initiate this mechanism. Detailed discussions of all aging mechanisms for aluminum-based poison materials are provided below.

3.4.2.1 General corrosion

Because aluminum is present as a continuous matrix (borated aluminum and aluminum metal-matrix composites) or used as an outer cladding (Boral®)), the degree of general corrosion of each of the neutron poison plate materials is considered to be largely governed by the corrosion of aluminum. As discussed in Section 3.2.3.1 for other aluminum components, aluminum forms a protective oxide film at temperatures below approximately 230 degrees C [446 degrees F]. Above this temperature, the protective film no longer forms if water or steam is present. As such, general corrosion of aluminum is possible if aluminum were exposed to moisture in the internal helium environment. However, there is very little residual water in the cask or canister internal environment following drying. Assuming a residual water content of 1 L [0.26 gal], Jung et al. (2013) calculated that oxidation of all aluminum in the basket assembly is limited to 0.54 g [0.019 oz], which is equivalent to a 2-μm [0.079-mils]-thick layer of aluminum over a surface area of 1,000 cm^2 [155 in^2]. Thus, the potential for material thinning from oxidation is a very small fraction of the aluminum poison materials used inside the system. As a result, general corrosion is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.4.2.2 Galvanic corrosion

Galvanic corrosion occurs when two dissimilar metals or conductive materials are in physical contact in the presence of a conducting solution (Baboian, 2003; Hack, 1993). The aluminum-based neutron poison materials used inside DSSs can be in galvanic contact with stainless steel, where aluminum is less noble.

As discussed above in the evaluation of general corrosion, there is very little residual water within a cask or canister following drying. Thus, there is a limited potential for the presence of a conducting solution that can support galvanic corrosion. As a result, loss of material due to galvanic corrosion is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.4.2.3 Wet corrosion and blistering

The core of aluminum-boron carbide laminate composites is not fully sintered and, as a result, can have a porosity of 1 to 8 percent with varying degrees of interconnectivity among pores. This may allow water ingress into the core, where the water can react with the aluminum to form aluminum oxide and hydrogen gas (EPRI, 2009; 2012). Blistering has been observed in the Boral® cladding in wet and dry storage applications. Tests simulating the wetting and vacuum drying cycles during canister closure operations show that Boral® can form blisters in the aluminum cladding because of water ingress through its exposed edges (EPRI, 2004). The blisters are characterized by a local area where the aluminum cladding separates from the underlying boron carbide-aluminum core, and the cladding is physically deformed outward.

Although wet corrosion and blistering may occur, this aging mechanism has not been observed to reduce the neutron absorbing capability of Boral® in spent fuel pool surveillance coupons (EPRI, 2009). It is important to note that, because only a trace amount of water will be left in a dry storage cask after dehydradation and helium backfill, the occurrence of wet corrosion and blistering will be minimal in a dry cask environment during the period of extended operation. Therefore, wet corrosion and blistering are not considered to be an aging mechanism requiring aging management and aging management is not required for Boral® in the DSSs with respect to criticality safety during the 60-year timeframe.

3.4.2.4 Boron depletion

Boron depletion refers to the loss of the capability of a material to absorb neutrons when the neutron fluence significantly consumes boron-10 atoms. Neutron poison plates typically contain 10^{19} to 10^{21} boron-10 atoms/cm^2 [6.5 × 10^{19} to 10^{21} boron-10 atoms/in^2] (EPRI, 2009). A neutron flux of 10^4–10^6 n/cm^2-s [6.5 × 10^4–6.5 × 10^6 n/in^2-s] is typical for dry cask storage (Sindelar et al., 2011). Under a neutron flux, boron-10 nuclei capture neutrons, yielding excited boron-11 nuclei, which, in turn, decay into high-energy alpha particles and lithium-7 nuclei. In this nuclear reaction, one neutron would deplete one boron-10 atom. At typical levels of neutron flux and boron-10 concentration, the neutron dose after 60 years would deplete at most 0.0002 percent of the available boron-10 atoms. Using the highest expected neutron flux and the lowest boron-10 concentration as a worst case scenario, only 0.02 percent of the available boron-10 atoms would be depleted after 60 years, which is too small to challenge the criticality control function of the neutron poisons. As such, boron depletion for borated aluminum alloys, aluminum metal matrix composites, and Boral® is not expected to result in significant changes in the criticality control function. As such, boron depletion is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Although the above generic evaluation does not identify boron depletion as a significant aging mechanism, the reviewer nevertheless should ensure that the renewal application addresses any depletion analyses that exist in the orginal design basis to consider the implication of extending the operating period to 60 years. Staff guidance for the review of such TLAAs is provided in NUREG–1927.

3.4.2.5 Creep

As discussed in Section 3.2.1.6, as a general rule of thumb, significant creep occurs at temperatures above $0.4T_m$, where T_m is the melting point of the metal in Kelvin (Cadek, 1988). At these temperatures, plastic deformation or distortion can occur over long times, even under stresses that normally would not be considered sufficient to cause yielding of the material. Because aluminum is present as a continuous matrix and as an external cladding in the neutron poison plates, and aluminum has a lower melting point than the other portions of the material microstructures (e.g., aluminum and titanium borides, boron carbides), the creep behavior of poison materials is considered to be governed by the behavior of aluminum. Applying the $0.4T_m$ rule, the critical creep temperature for aluminum is 100 degrees C [212 degrees F].

The highest temperatures within DSSs are at locations close to the fuel rods. For example, the maximum expected temperature of the cladding on the fuel rods has been estimated to be 400 degrees C [752 degrees F] at the beginning of the storage period, and the cladding temperatures are expected to decrease to approximately 266 degrees C [510 degrees F] after 20 years and 127 degrees C [261 degrees F] after 60 years (Jung et al., 2013). These estimates depend on many factors, such as the initial heat load of the SNF. It is apparent from these temperatures that subcomponents within the cask or canister could be exposed to temperatures above the minimum creep temperatures for aluminum during at least the first 40 years.

Because temperatures within DSSs have the potential to exceed the minimum creep temperature of aluminum, it is necessary to consider the load applied to the subcomponent to determine whether significant creep deformation will occur, as well as the specific application to determine whether the creep affects safety. Typically, neutron poison plates do not serve a structural function and are thus not expected to be under loads other than their own weight. Also, in many instances, their weight is also supported by adjacent structures. For example, the neutron poison plates in the Holtec HI-STORM 100 system are completely enclosed in stainless steel sheating (Holtec International, 2014). Due to the minimal applied loads and presence of adjacent supporting structures, the impact of creep on the criticality control function of the neutron poisons is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.4.2.6 Thermal aging

Prolonged exposure to elevated temperatures can lead to a loss of fracture toughness and ductility in some materials as a result of changes to their microstructure. Testing of aluminum-based neutron poison plates, however, has shown that these materials typically increase in ductility when they are aged at high temperatures. For example, a series of elevated temperature tensile tests on an aluminum metal-matrix composite (METAMIC™) found an increase in elongation to break (a measure of ductility) when the material was aged at 399 degrees C [750 degrees F] for 8,523 hours (EPRI, 2009). These and other material qualification tests performed on neutron poisons demonstrate that microstructural changes induced by aging typically make the aluminum softer and more ductile as it is annealed, while the boride and carbide particulates are thermally stable at cask internal temperatures.

Also, as discussed above for the creep mechanism, decreases in strength due to thermal aging are not expected to affect the criticality control function of the poison plates, because they typically do not serve a structural function and may be supported by adjacent structures. Consequently, thermal aging of neutron poison materials is not considered to be credible, and therefore, aging management is not required over the 60-year timeframe.

3.4.2.7 Radiation embrittlement

As discussed in Section 3.4.1.4 above, embrittlement of metals may occur under exposure to radiation. Neutron radiation (rather than gamma radiation) has the greatest potential to cause this phenomenon.

Depending on the neutron fluence, radiation can cause changes in mechanical properties such as loss of ductility, fracture toughness, and resistance to cracking. Farrell and King (1973) showed that pure aluminum had increased strength but decreased ductility after being irradiated to fast neutron fluences (energy greater than 0.1 MeV) in the range of 1 to 3 × 10^{22} n/cm^2 [6.5 to 19.4 × 10^{22} n/in^2] from a research reactor for 8 years. However, these radiation levels are six orders of magnitude higher than the estimated fluence after dry storage for 100 years as discussed in Section 3.2.1.9.

Some results from radiation testing of aluminum-based neutron poisons are reported in the literature (EPRI, 2009). Gamma, thermal neutron, and fast neutron radiation testing of Boral® in water was performed for 9 years. With exposures of to up to 7 × 10^{11} rad of gamma, 3.6 × 10^{18} n/cm^2 [2.3 × 10^{19} n/in^2] fast neutron fluence, and 2.7 × 10^{19} n/cm^2 [1.7 × 10^{20} n/in^2] thermal neutron fluence, the specimen showed no change in ultimate strength and no other signs of physical deterioration, except for severe oxidation because of the presence of water.

Also, radiation testing of a sintered composite subjected to up to 1.5 × 10^{20} n/cm^2 [9.7 × 10^{20} n/in^2] fast neutron fluence and a maximum of 3.8 × 10^{11} rad gamma exposure showed little change in the yield strength and ultimate strength (EPRI, 2009). Finally, neutron radiation of borated aluminum to fluences of 10^{17} n/cm^2 [6.5 × 10^{17} n/in^2] showed no dimensional change or radiation damage (EPRI, 2009). These test conditions are expected to be more severe than those experienced by the aluminum-based neutron poison materials in the extended storage application (EPRI, 2009). Therefore, radiation embrittlement of borated aluminum alloys, aluminum metal-matrix composites, and Boral® is not expected to be credible. Consequently, aging management is not required during the 60-year timeframe.

3.4.3 References

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3.5 Concrete overpacks, support pads, and ceramic fiber insulation

Concrete overpacks and support pads include various structural subcomponents constructed of concrete and reinforcing steel, as well as pad-supporting materials constructed of engineered fill, natural soil, or treated soil. These subcomponents may be exposed to several environments, such as outdoor air, groundwater or soil, and flowing water, or they may be sheltered or embedded in concrete or steel. The environment may also include elevated temperatures due to heat released by the SNF and radiation, with dose rates depending on the SNF characteristics (e.g., burnup and age of fuel), exposure time, and location of the subcomponent.

Potential aging mechanisms for the concrete overpack and pad subcomponents were identified from reviews of gap assessments of DSSs, relevant technical literature, American Concrete Institute (ACI) guides and reports, and operating experience from nuclear and nonnuclear applications (NRC, 2014, 2011a, 2010a; Chopra et al., 2014; Hanson et al., 2011; NWTRB, 2010). Additional mechanisms were identified during a recent NRC concrete expert panel workshop (NRC, 2015). Thermal, mechanical, chemical, and irradiation-induced degradation mechanisms were identified as follows:

- freeze and thaw
- creep
- reaction with aggregates
- aggressive chemical attack
- corrosion of reinforcing steel
- differential settlement
- shrinkage
- leaching of calcium hydroxide
- radiation damage
- fatigue
- dehydration at high temperature
- microbiological degradation
- delayed ettringite formation
- salt scaling

In addition, a review of known degradation modes for ceramic fiber insulation was performed, which resulted in consideration of the following:

- radiation damage
- moisture absorption

Potential mechanisms were refined by considering the thermal, mechanical, chemical, and irradiation conditions specific to each subcomponent. This process eliminated several mechanisms from consideration for some subcomponents in the AMR tables in Chapter 4. Detailed discussions regarding potential aging mechanisms for each material and the technical bases for those requiring aging management are included in the following sections.

These discussions do not consider potential synergistic effects, if any, due to coupled degradation mechanisms. Coupled degradation mechanisms in concrete refer to degradation modes that can interact, affecting their relative times for initiation and progression (e.g., freeze-thaw cracking that leads to water ingress and subsequent leaching of calcium hydroxide). Few in-depth studies have been published on the effects of concrete damage caused by these potential coupled degradation mechanisms. However, the staff expects that an AMP is an adequate approach for addressing potential synergistic effects due to coupled degradation mechanisms. The example of an AMP for concrete structures in Chapter 6 relies on the licensee's corrective action program to ensure that conditions that may lead to a loss of intended function will be reviewed and dispositioned by trained personnel. If a particular aging effect is detected, part of the licensee's corrective action may include a root-cause evaluation to determine the cause of the aging effect. If the root-cause evaluation determines that the rate of degradation is being accelerated by the effects of coupled degradation modes, followup corrective actions may include a review of the inspection or monitoring procedures to ensure that aging management activities remain adequate for the remaining period of extended operation.

3.5.1 Concrete

3.5.1.1 Freeze and thaw

Concretes exposed to outdoor and groundwater/soil (below-grade) environments above the freeze line

Concretes that are nearly or fully saturated with water can be damaged by repeated freezing and thawing cycles in environments with weathering indexes (i.e., the product of the average annual number of freezing cycle days and the average annual winter rainfall in inches) on the order of 100 day-in/yr or greater (NRC, 2010a). For environments with weathering indexes less than 100 day-in/yr, freeze and thaw degradation is not considered to be significant. The weathering index for the continental United States and adequate data sourcing for determining the weathering for any locality can be found in ASTM C216 (ASTM, 2016). For below-grade concrete structures above the freeze line, water that resides in soil can also be subject to freezing conditions, potentially promoting freeze and thaw damage.

Freeze and thaw damage has been observed in outdoor concrete structures in nuclear power plants (NRC, 1995, 2012). Because water expands when freezing, fully or mostly saturated concrete will experience internal stresses from the expanding ice, which can cause concrete cracking or scaling when pressures exceed the concrete tensile strength (ACI, 2008c; Pigeon, 1994; Marchand et al., 1994; Sawan, 1987; Fagerlund,1977).

The degradation mode would initiate at the outer concrete surface of the DSS exposed to outdoor environments, primarily at horizontal surfaces where water ponding can occur. Operating experience has identified freeze and thaw damage in the roofs of the concrete storage modules at the Three Mile Island Unit 2 (TMI-2) and the Millstone independent spent fuel storage installation (ISFSI) (NRC, 2012).

Therefore, freeze and thaw damage is considered credible in concrete exposed to outdoor and groundwater or soil (below-grade) environments above the freeze line, and aging management is required during the 60-year timeframe.

Concretes exposed to sheltered environments, fully encased (lined) in steel, and exposed to groundwater/soil (below-grade) environments under the freeze line

Freeze and thaw degradation of concrete exposed to sheltered environments with low water availability is not considered credible; the heat load from the fuel in the DSS is expected to aid in drying the interior concrete surfaces of the overpacks, preventing freeze and thaw damage.

Freeze and thaw degradation of concrete exposed to groundwater or soil (below-grade) environments at temperatures above freezing is not considered credible.

Freeze and thaw damage also is not considered credible for concrete fully encased in metallic liners (not in direct contact with outdoor environments or proven to be protected from water ingress); the lack of water transfer from the outside environment into the concrete prevents the degradation mechanism.

Therefore, aging management of concrete for freeze and thaw degradation in these environments is not required.

3.5.1.2 Creep

Creep in concrete is the time-dependent deformation resulting from sustained loads (Wang and Salmon, 1998). Cement paste in concrete exhibits creep due to its porous structure and a large internal surface area that is sensitive to water movements. Creep manifests as cracking on the concrete outer surfaces and causes redistributions of internal forces. Factors affecting creep are concrete constituents (composition and fineness of the cement; admixtures; and size, grading, and mineral content of aggregates), water content and water-cement ratio, curing temperature, relative humidity, concrete age at loading, duration and magnitude of loading, surface-volume ratio, and slump (Wang and Salmon, 1998; Neville and Dilger, 1970). However, the most important parameter controlling creep is concrete sustained loading. Creep increases with increasing load and temperature (McDonald, 1972). However, the creep rate decreases exponentially with time (Branson, 1977; NRC, 2014; Wang and Salmon, 1998). In summary, in the case of a given concrete mix design, concrete creep is generally understood to be a phenomenon that would affect concrete structures early in the service life under sustained loading. Thus, the age of concrete and the magnitude and duration of sustained loading are the primary factors that determine the magnitude of the creep of concrete (Neville and Dilger, 1970). For example, if a sustained load is applied on 2-year-old and 40-year-old concrete, the 2-year-old concrete will have significantly more creep. Also, the creep in concrete could largely be mitigated by proper design practices, in accordance with ACI 318-05 (ACI, 2005) or ACI 349-06 (ACI, 2007). Furthermore, creep-induced concrete cracks are not generally large enough to reduce the compressive strength of concrete, cause deterioration of concrete, or cause exposure of reinforcing steel to the environment. In a DSS, the initial sustained load is normally low, and no significant change of load is expected during the 40-year timeframe beyond initial licensing. Thus, creep is not considered credible for any environment, and aging management is not required during the 60-year timeframe.

3.5.1.3 Reaction with aggregates

The two most common alkali-aggregate reactions are alkali-silica reaction (ASR) and alkali-carbonate reaction, with ASR being the most common and damaging. ASR is a chemical reaction between hydroxyl ions (present in the alkaline cement pore solution) and reactive forms of silica present in some aggregates (e.g., opal, chert, chalcedony, tridymide, cristabolite, strained quartz). An aggregate that presents a large surface area for reaction (i.e., amorphous, glassy) is susceptible to ASR (Poole, 1992). The resulting chemical reaction produces an alkali-silica gel that swells with the absorption of moisture, exerting expansive pressures within the concrete (Figg, 1987). ASR damage in the concrete manifests as a characteristic map cracking on the concrete surface (ACI, 2008a). The internal damage results in the degradation of concrete mechanical properties, and in severe cases, the expansion can result in undesirable dimensional changes and popouts. In reinforced concrete, cracks tend to align parallel to the direction of maximum restraint and rarely progress below the level of the reinforcement. In general, ASR is a slow degradation mechanism that can cause serviceability issues and may exacerbate other deterioration mechanisms.

The requisite conditions for initiation and propagation of ASR include (i) a sufficiently high alkali content of the cement (or alkali from other sources, such as deicing salts, seawater, and groundwater), (ii) a reactive aggregate, and (iii) available moisture, generally accepted to be relative humidity greater than 80 percent (Pedneault, 1996; Stark, 1991). A study by the California Department of Transportation (Glauz et al., 1996) revealed that ASR increases proportionally to the cement content, alkali content greater than 0.6 percent can accelerate ASR, high calcium oxide content can promote ASR, and the use of various types of admixtures in certain doses can mitigate ASR (ACI, 2008a; ASTM, 1998). At higher concentrations of alkali hydroxides, even the more stable forms of silica are susceptible to ASR attack (Xu, 1987). Repeated cycles of wetting and drying can accelerate ASR (ACI, 1998). As a result, it is desirable to minimize both available moisture and wet-dry cycles by providing good drainage. Moreover, concretes exposed to warm environments are more susceptible to ASR than those exposed to colder environments (Perenchio et al., 1991).

As mentioned earlier, ASR is generally a slow degradation mechanism. ASR may take from 3 to more than 25 years to develop in concrete structures, depending on the nature (reactivity level) of the aggregates, the moisture and temperature conditions to which the structures are exposed, and the concrete alkali content (Thomas et al., 2013). The delay in exhibiting deterioration indicates that there may be less reactive forms of silica that can eventually cause deterioration (Mindess and Young, 1981). Recent operating experience has revealed degradation of the concrete in the Seabrook reactor containment as a result of ASR (NRC, 2011b). The concrete used at the Seabrook plant passed all industry standard ASR screening tests (ASTM, 2007, 2012) at the time of construction. However, ASR-induced degradation was identified in August 2010. In addition, ASR screening tests are not conducted on each aggregate source but rather in select batches, which increases the risk for use of aggregates of different reactivities when procured from different sources. Due to the uncertainties in screening tests that can effectively be used to eliminate the potential for ASR and previous ASR operating experience at a nuclear facility, the aging mechanism is considered credible in concrete exposed to any environment with available moisture, and therefore, aging management is required during the 60-year timeframe.

3.5.1.4 Differential settlement

Differential settlement is a result of the uneven deformation of the supporting foundation soil (Das, 1999; NAVFAC, 1986). The factors affecting structural settlement include the type of foundation soil (e.g., clayey soil, sandy soil) and its physical properties, thickness of soil layers, water-table level, depth of foundation mat below the ground surface, liquefaction during seismic events, and load. Differential settlement, which causes distortion (loss of form) and damage (cracking) to concrete structures, is a function of the uniformity of the soil, stiffness of the structure, stiffness of the soil, and distribution of loads within the structure (U.S. Department of the Army, 1990; NAVFAC, 1996).

The settlement of saturated cohesive soil consists of three components: (1) immediate settlement occurring due to the applied load, (2) consolidation settlement occurring gradually due to dissipation of the excess pore pressures generated by the applied load, and (3) secondary compression that depends on the composition and structure of the soil skeleton (NAVFAC, 1986). The settlement of course-grained granular soils subject to applied load occurs immediately, primarily from the compression of the soil skeleton due to rearrangement of particles. However, most settlement issues involving a combination of immediate settlement and progressing long-term settlement are typically discovered in less than 1 year of construction.

Differential settlement is addressed during the design-basis calculations. The analyses generally include calculations to predict differential settlement based on the sequential DSS placement; the analyses are used to determine an optimum DSS placement sequence to limit differential settlement of the ISFSI support pad. However, operating experience has shown that it can occur; periodic walkdowns ensure these limited occurrences are evaluated on a case-by-case basis. NUREG–1522, “Assessment of In-service Conditions of Safety-Related Nuclear Plant Structures” (NRC, 1995), stated that foundation settlement of concrete structures at Point Beach and Beaver Valley, inspected during walkdowns, experienced appreciable differential settlement. In addition, the loads on the concrete pad are expected to increase over time as more loaded DSSs are placed on the pad. Therefore, differential settlement of concretes exposed to sheltered, outdoor, and groundwater or soil (below-grade) environments is considered credible, and aging management is required during the 60-year timeframe.

3.5.1.5 Aggressive chemical attack

The intrusion of aggressive ions or acids into the pore network of the concrete can cause various degradation phenomena. The aggressive chemical attack typically originates from an external source of sulfate or magnesium ions as well as acidic environmental conditions. Depending on the type of aggressive chemical, the degradation of concrete can manifest in the form of cracking, loss of strength, concrete spalling and scaling, and reduction in concrete pH.

Concretes exposed to outdoor and groundwater/soil (below-grade) environments

External sulfate attack

External sulfate attack is a process whereby ions in species such as K_2SO_4, Na_2SO_4, $CaSO_4$, and $MgSO_4$, which are present in groundwater, seawater, and rainwater, penetrate the concrete and chemically react with alkali and calcium ions to form a precipitate of calcium sulfate in addition to other forms of calcium and sulfate-based compounds (e.g., ettringite). The manifestation of sulfate attack is cracking, increase in concrete porosity and permeability, loss of strength, and surface scaling generated by the expansion associated with the formation of ettringite within the concrete and the pressure generated by the precipitated calcium and sulfate-base compounds inside the concrete pore network (Poe, 1998; NWTRB, 2010). Unlike the alkali sulfates, no decalcification of the calcium silicate hydrate phase occurs in the $CaSO_4$ attack. On the other hand, the $MgSO_4$ attack is significantly faster and more thorough than the attack by the other sulfate compounds because of the limited solubility of magnesium hydroxide ($Mg(OH)_2$) in the high pH of concrete (Drimalas et al., 2010). In addition, magnesium ions present in deicing salts can react with calcium silicate hydrate, gradually converting it to magnesium silicate hydrate, which is not cementitious in nature.

A service life model for sulfate attack in concrete was developed by Atkinson and Hearne (1990). Cases of sulfate attack in the field are fairly uncommon, mainly because most transportation regulatory agencies have adopted specifications aimed at preventing this damage mode
(Weiss et al., 2009; Van Dam and Peshkin, 2009). In particular, degradation due to external sulfate attack has not been reported in nuclear applications. Atkinson and Hearne (1990) developed a concrete service life model to assess degradation due to sulfate attack. Using aggressive soil and groundwater conditions (sulfate concentration of 1,500 ppm as specified in ASME Code Section XI, Subsection IWL (ASME, 1995)) and typical concrete properties (i.e., elastic modulus, roughness factor, Poisson's ratio, and concrete porosity), the model predicts that sulfate damage can occur within 60 years of exposure (Berntz et al., 2001).

Magnesium attack

Magnesium ions can rapidly replace calcium ions in the silica hydrate compounds. In groundwater, magnesium ions are commonly found in the form of $MgSO_4$. The magnesium ion attack is more commonly observed in arid western U.S. areas and in below-grade structures. At present, there is no stipulation on the threshold concentration of magnesium ions needed to promote damage to concrete structures for nuclear and nonnuclear applications. Because magnesium attack could be part of the sulfate attack, the timeframe implications and exposure conditions are expected to be comparable to those of sulfate attack.

Acid attack

Acids with a pH less than 3 can dissolve both hydrated and unhydrated cement compounds (e.g., calcium hydroxide, calcium silicate hydrates, and calcium aluminate hydrates) as well as calcareous aggregate in concrete without any significant expansion reaction (Gutt and Harrison, 1997; Mehta, 1986). In most cases, the chemical reaction forms water-soluble calcium compounds, which are then leached away by aqueous solutions. The dissolution of concrete commences at the surface and propagates inward as the concrete degrades. The signs of acidic attack are loss of alkalinity (also disturbing of electrochemical passive conditions for the embedded steel reinforcement), loss of material (i.e., concrete cover), and loss of strength.

The extent and rate of concrete degradation depends on the type, concentration and pH of the acidic solution, concrete permeability, calcium content in the cement, the water-to-cement ratio, and the type of cement and mineral admixtures (Pavlik and Uncik, 1997). Sulfuric acid is particularly aggressive to concrete, because the calcium sulfate formed from the acid reaction will also deteriorate concrete via sulfate attack (Pavlik, 1994). Even slightly acidic solutions that are lime deficient can attack concrete by dissolving calcium from the paste, leaving behind a deteriorated paste consisting primarily of silica gel.

Acids can come from groundwater as well as from acid rain containing SO_2, NO_x, and HCl from polluted regions, which can compromise the durability of concrete (Webster and Kukacka, 2009). Ueda et al. (2001) proposed a model for acid rain deterioration, which is dependent on the amount of acid absorption into the concrete, type of acid, mix proportion, and contact time or interval of rainfalls. The model can predict the depth of concrete damage as a function of environmental pH. A study by Manjeeth and Rama (2015) found that the compressive strength and mass loss of concrete samples decreased after 28 days of exposure to sulfuric acid solutions with pH ranging from 1 to 7. As such, this degradation mode is expected to affect the concrete shortly after the concrete surface is in contact with the acid solution.

In summary, aggressive chemical attack of concretes exposed to outdoor and groundwater or soil (below-grade) environments is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Concretes exposed to sheltered and fully encased (lined) in steel environments

With regard to concrete in sheltered environments and fully encased (lined) in steel, external sources of sulfate, magnesium, and acid entering concrete are considered to be insignificant. In addition, the heat load from the fuel in the DSS is expected to aid in drying the interior concrete surfaces, thus decreasing water availability at the concrete surface, which is necessary to promote this degradation mode. Thus, aggressive chemical attack of sheltered and fully encased (lined) concrete is not considered credible, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.6 Corrosion of reinforcing steel

Concretes exposed to outdoor and groundwater/soil (below-grade) environments

Corrosion of the reinforcing steel embedded in the concrete is mainly caused by the presence of chloride ions in the concrete pore solution and carbonation of the concrete. Chloride attack of concrete structures is well established in the literature (Cheung et al., 2009). The highly alkaline environment provided by the concrete (normally with pore water pH>13.0) results in the formation of a metal-adherent oxide film on the reinforcement steel bar surface, which passivates the steel (Page, 1982). However, chloride ions may penetrate the concrete matrix and break down the steel passive layer, once the chloride concentration at the reinforcing steel surface exceeds a threshold value, triggering corrosion of the reinforcing steel and shortening the service life of a concrete structure. For instance, chlorides may already exist at low levels within the base mix constituents. In most practical situations, chloride ions penetrate from the outside environment, such as when using deicing salts, from groundwater, and in marine environments (Tang and Sandberg, 1996). The presence of corrosion products at the steel surface can generate internal stresses within the concrete matrix, causing cracks and spalling of the concrete cover with consequent structural damage.

The threshold chloride concentration in concrete required to promote corrosion of the reinforcing steel depends on the pH of the concrete pore solution. The onset of corrosion can be enhanced when acid attack or concrete carbonation[1] reduces the concrete pH at the steel surface. Thus, the chloride-to-hydroxide ratio is an important parameter in evaluating the steel corrosion. The present literature does not provide a clear agreement on the value of the critical chloride ion concentration required for corrosion initiation. Glass and Buenfeld (1997) have reviewed the chloride threshold values reported for steel embedded in concrete structures. From this investigation, it was concluded that a universal, well-defined chloride threshold value does not exist. The lowest limit of chloride threshold value in concrete ranged from 0.2 to 2.5 percent (by weight of cement). Factors such as the chemical composition of the rebar, as well as its

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[1] Carbonation results from the chemical reaction between the hydrated cement material and atmospheric carbon dioxide, which lowers the pH of the concrete and reduces the passivation effect of calcium hydroxide in preventing the corrosion of reinforcing steel. The carbonation rate depends on the external CO_2 concentration, concrete type, temperature, time of wetness of the concrete surface, and degree of moisture (Bertolini et al., 2004).

surface roughness, can influence the chloride threshold (Szklarska-Smialowska, 1986). Groundwater aggressiveness is defined based on the chloride threshold concentration of 500 ppm [milligram (mg)/kilogram (kg)] with a pH less than 5.5 (ASME, 1995, Section XI, Subsection IWL). This value is consistent with those recommended in ACI 201.2R-08 (ACI, 2008c).

Concrete durability is directly related to the quality of the concrete, the external concentration of chlorides on the concrete surface, and the reinforcement material. The service life of concretes exposed to chloride attack depends on the concrete cover, the surface chloride concentration, the chloride diffusion coefficient, the type of cementitious material, and the reinforcing steel material. Several service life models have been proposed to determine the durability of concrete subject to chloride-induced corrosion (Schiessl et al., 2006; DuraCrete, 2000; Berntz et al., 2001). For example, for a constant surface chloride concentration of 0.05 percent by weight of concrete (i.e., the maximum chloride concentration in soil and groundwater per ASME Code Section XI, Subsection IWL ASME, (ASME, 1995)), a 2.54-cm [1-in] concrete cover, and a chloride threshold of 0.03 percent by weight of concrete, the onset of chloride-induced corrosion in concrete occurs in about 6, 20, and 120 years for constant chloride diffusion coefficients of 6.45×10^{-7} cm^2/second (sec) [10^{-7} in^2/sec] (poor concrete quality), 6.45×10^{-8} cm^2/sec [10^{-8} in^2/sec] (moderate concrete quality), and 6.45×10^{-9} cm^2/sec [10^{-9} in^2/sec] (good concrete quality), respectively (Berntz et al., 2001).

Although no cases of corrosion-induced damage have been reported, the results of the durability model presented by Berntz et al. (2001) show that corrosion of the reinforcing steel in concrete can potentially initiate and propagate within the 60-year timeframe for concretes of moderate to low quality. Thus, corrosion of reinforcing steel in concrete exposed to outdoor and groundwater or soil (below-grade) environments is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Concretes exposed to sheltered environments and fully encased (lined) in steel

Chloride ingress is expected to be insignificant for steel reinforcement embedded in concrete in sheltered environments with limited exposure to water. In addition, the heat load from the fuel in the DSS is expected to aid in drying the interior concrete surfaces, thus decreasing water availability at the concrete surface, which is necessary to promote this degradation mode. Chloride ingress will also be impeded in concrete fully encased (lined) in steel. Thus, corrosion of reinforcing steel is not considered credible for concrete in these environments, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.7 Shrinkage

Shrinkage occurs when hardened concrete dries from a saturated condition to a state of equilibrium in about 50 percent relative humidity (NRC, 2012). As excess concrete water evaporates, tensile stresses are induced in the concrete due to internal pressure from the capillary action of water movement, which results in cracking. The factors affecting shrinkage are cement content, water-to-cement ratio, degree of hydration, elastic modulus of aggregates, amount and characteristics of concrete admixtures, temperature and humidity during curing, and size and shape of concrete (NRC, 2014; Branson, 1977; Mindess and Young, 1981).

The maximum shrinkage is in the range of 400×10^{-6} to 780×10^{-6} cm/cm [400×10^{-6} to 780×10^{-6} in/in] (NRC, 2014; Branson, 1977) and decreases exponentially with time (Branson, 1977). Shrinkage of concrete occurs initially during curing, which can be controlled through concrete formulation and the density and distribution of internal reinforcement (ACI, 2005, 2007). According to ACI 209R-92 (ACI, 2008b), over 90 percent of the shrinkage occurs during the first year, reaching 98 percent by the end of the first 5 years. Thus, shrinkage is not expected to influence concrete performance after the initial storage or licensing period, because most of the shrinkage will take place early on in the life of the concrete. As a result, shrinkage of concretes exposed to sheltered, outdoor, groundwater or soil (below grade), and fully encased environments is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.8 Leaching of calcium hydroxide

Concretes exposed to outdoor, sheltered, and groundwater/soil (below-grade) environments

A constant or intermittent flux of water through a concrete surface can result in the removal or leaching of calcium hydroxide (Hanson et al., 2011). Calcium hydroxide leaching is observed in the form of white leachate deposits (calcium carbonate) on the concrete surface. Calcium hydroxide leaching causes loss of concrete strength, converting the cement into gels that have no strength. Leaching also increases the concrete porosity and permeability, making it more susceptible to other forms of aggressive attack. In addition, leaching of calcium hydroxide in concrete lowers the concrete pH, affecting the integrity of the protective oxide film of the reinforcing steel (EPRI, 2007).

The extent of the leaching depends on the environmental salt content and temperature (NRC, 2011a), and it can take place above and below ground. However, the leaching rate is generally slow and controlled by diffusion (Berner, 1992). For example, interior inspections conducted at the Calvert Cliffs ISFSI revealed the presence of white-colored stalactite debris in the gap between the heat shield and the concrete ceiling of two sheltered DSS concrete structures after 15–20 years in service. Stalactites are formed when water leaches calcium hydroxide out of the concrete, which precipitates as calcium carbonate on contact with carbon dioxide in the air. The licensee concluded that water entering the outlet vent stack promoted calcium hydroxide leaching (Gellrich, 2012). Other exterior inspections conducted at the TMI-2 ISFSI revealed efflorescence growth on multiple DSS concrete structures exposed to an outdoor environment. The licensee concluded that the efflorescence deposits were formed by water entering freeze and thaw cracks in the anchor blockout holes on the roof of the HSMs. The licensee conducted core sample testing to verify concrete compressive strength. Therefore, operating experience indicates that leaching of calcium hydroxide is a mechanism that can be exacerbated by other degradation mechanisms or designs that do not adequately prevent ingress of precipitation into the sheltered structure. As such, leaching of calcium hydroxide in concrete exposed to outdoor, sheltered, and groundwater or soil (below-grade) environments is considered to be credible, and therefore, aging management is required during the 60-year timeframe.

Concretes fully encased (lined) in steel

Leaching of calcium hydroxide is not considered a credible mechanism for concrete fully encased (lined) in steel because of the lack of water ingress, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.9 Radiation damage

Radiation effects on concrete properties will depend on the gamma and neutron radiation doses, temperature, and exposure period. Gamma radiation can decompose and evaporate water in concrete (Bouniol and Aspart, 1998). Because most of the water is contained in the cement paste, the effect of gamma radiation on cement paste is more significant than on the aggregates. Gamma radiation can also decompose the SiO bond within calcium silicate hydrate (Kontani et al., 2010). Neutron radiation deteriorates concrete by reducing stiffness, forming cracks by swelling, and changing the microstructure of the aggregates. This consequently reduces concrete strength (Kontani et al., 2010). The changes in aggregate microstructure also can lead to higher reactivity of aggregates to certain aggressive chemicals.

NUREG/CR-7171, "A Review of the Effects of Radiation on Microstructure and Properties of Concretes Used in Nuclear Power Plants," provides a comprehensive review of the effects of gamma and neutron radiation on the microstructure and properties of concrete used in nuclear power plants (NRC, 2013). Concrete structures have been regarded as being sound as long as the cumulative radiation does not exceed critical levels over the life of the structure. In general, the critical radiation levels to reduce concrete strength and elastic modulus are considered to be approximately 1×10^{19} n/cm^2 [6.5×10^{19} n/in^2] for fast neutrons (neutron energy >1 MeV) and 1-2 × 10^{10} rad [1-2 × 10^{8} grays] for gamma rays (Hilsdorf et al., 1978; EPRI, 2012; IAEA, 1998; ASME, 2007).

As discussed in Section 3.2.1.9, the maximum potential accumulated neutron fluence on DSS basket components after 100 years was calculated to be 2.63×10^{16} n/cm^2 [1.70×10^{17} n/in^2], which is three orders of magnitude below the level that would lead to a reduction of concrete strength and elastic modulus. The gamma dose is also expected to be several orders of magnitude less than the limits defined in the above references, per the specific DSS design bases. Thus, radiation damage is not considered credible for concrete, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.10 Fatigue

Concrete fatigue strength is defined as the maximum stress that the concrete can sustain without failure under a given number of stress cycles (NRC, 2014). Because dry storage is a static application, mechanical cyclic loading is not expected. However, restraint of the concrete from expanding and contracting as it is exposed to rapid changes in temperature will lead to internal stresses in the structure. If the changes in temperature are severe and the resulting strains are sufficient, local plastic deformation can occur. Repeated application of this thermal loading can lead to crack initiation and propagation in low-cycle fatigue.

Concrete fatigue in the DSS reinforced concrete may be caused by diurnal and seasonal temperature gradients through the wall of the DSS assembly. The inside surface of the concrete wall is hotter than the outside surface of the concrete wall, which causes compressive stresses in the DSS concrete near the inside of the concrete wall and tensile stresses in the rebar near the outside of the concrete wall.

Extreme seasonal temperature variations are expected to be significantly higher than diurnal variations; these would be capable of producing higher cyclic stress amplitudes. Assuming ambient temperatures of -40 degrees C [−40 degrees F] (winter) and 52 degrees C [125 degrees F] (summer), the maximum thermal gradient across the DSS concrete is expected to be less than 16 degrees C [60 degrees F]. The number of extreme seasonal temperature cycles, conservatively postulated to occur 10 times per year, is 600 over 60 years.

Diurnal temperature fluctuations in ambient air temperatures are assumed to occur once per day. For conservatism, it is assumed that the diurnal temperature fluctuations are 25 degrees C (the largest mean daily change of temperature in the United States). Therefore, the total number of thermal cycles due to diurnal temperature variations in ambient temperatures over 60 years is 21,900 thermal cycles. Thus, the total number of thermal cycles due to seasonal and daily variations over 60 years is 22,500 cycles. The thermally induced stress, σ, defined in Section 3.2.1.7, can be used to determine the stress in the concrete during each temperature cycle. Using a thermal expansion coefficient of 1.1×10^{-5} cm/cm/degrees C [6.5×10^{-6} in/in/degrees F] and an elastic modulus of 2.764×10^{4} megapascals (MPa) [4.035×10^{3} ksi], which are typical for concretes, the computed values of σ are 7.53 MPa [1.09 ksi] and 9.99 MPa [1.45 ksi] for the diurnal and seasonal temperature fluctuations, respectively.

The seasonal change in stress is assumed bounding for the cumulative number of cycles of both diurnal and seasonal temperature fluctuations. Assuming that these cyclic stresses are the only cyclic mechanical loading experienced by the DSS (an adequate assumption for a passive system), the ratio of the concrete compressive stress to its design strength is less than 0.29 (i.e., 1.45 ksi/5 ksi). This calculated ratio at 22,500 cycles is lower than the lowest stress/cycles-to-failure (S-N) curve for concrete reported in ACI 215R (ACI, 1997). Thus, fatigue of concrete exposed to sheltered, outdoor, groundwater or soil (below-grade), and fully encased environments is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

Notwithstanding the conclusion above, the NRC reviewer must review any fatigue analyses for concrete structures contained in the applicant’s original design-bases documents to determine whether the renewal application adequately addresses the implications of extending the operating period to 60 years. This reexamination of the original fatigue analyses should be defined as TLAAs in the renewal application. The staff’s guidance for the review of TLAAs is provided in NUREG–1927, Revision 1, and is summarized in Chapter 5 of this report.

3.5.1.11 Dehydration at high temperature

Exposure of concrete to elevated temperatures can affect its mechanical and physical properties (Phan and Carino, 2000). It is well known that concretes can degrade at high temperatures due to dehydration of the hydrated cement paste, thermal incompatibility between the cement and aggregates, and physicochemical deterioration of the aggregates (NRC, 2006). As the temperature increases to about 105 degrees C [221 degrees F], all evaporable water is removed from the concrete. At temperatures above 105 degrees C [221 degrees F], the strongly absorbed and chemically combined water are gradually lost, with the dehydration essentially complete at 850 degrees C [1,562 degrees F] (Harmathy, 1970). High-temperature degradation in concrete manifests as a change in compressive strength and stiffness, as well as an increase in concrete shrinkage and transient creep, resulting in the formation of cracks (Naus, 1981, 1988; Schneider et al., 1981). The effect of the elevated temperature is most significant on the concrete’s modulus of elasticity, which can decrease up to 40 percent (Freskakis, 1979). Concretes in the temperature range of 20 to 200 degrees C [68 to 392 degrees F] show small changes in compressive strength. Beyond 350 degrees C [662 degrees F], concrete compressive strength decreases rapidly (NRC, 2006).

NUREG–1536, “Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility” (NRC, 2010b), provides staff guidance for acceptable temperature limits during operation of DSS concrete structures. By design, general or local concrete temperatures should be kept below 93 degrees C [200 degrees F] to avoid mechanical deterioration. For DSS concrete designs that satisfy additional acceptance criteria, the maximum temperature during operation can exceed 93 degrees C [200 degrees F] but should remain less than 149 degrees C [300 degrees F]. Therefore, the effects of thermal dehydration are addressed during the initial ISFSI licensing or DSS approval. Because the fuel temperature decreases over time, the design temperature considerations in NUREG–1536 are expected to continue to be adequate. Thus, dehydration of concrete at high temperature is not considered to be credible in sheltered, outdoor, groundwater or soil (below-grade), and fully encased (lined) environments, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.12 Microbiological degradation

Concretes exposed to groundwater/soil (below-grade) environments

Biodeterioration is caused by colonization of microbes and microorganisms that grow on concrete surfaces that offer favorable environmental conditions (e.g., available moisture, near neutral pH, presence of nutrients). Conducive environments may have elevated relative humidity (i.e., greater than about 60 percent), long cycles of humidification and drying, freezing and thawing, high carbon dioxide concentrations, high concentrations of chloride ions or other salts, or high concentrations of sulfates and small amounts of acids (Wei et al., 2013). According to Sanchez-Silva and Rosowsky (2008), biodeterioration may lead to reduction of the protective cover depth and increase both concrete porosity and the transport of aggressive chemicals. In addition, this degradation mode can promote a reduction in concrete pH, loss of concrete strength, and spalling/scaling.

Evidence shows that a wide variety of organisms can cause concrete deterioration in polluted soils and groundwater. The biodeterioration of concrete typically is confined to the surface. The rate of deterioration is slow, but the degradation mode has been observed within 40 years of exposure (Hu et al., 2011). Recent observations in Texas, Alabama, Georgia, and Mississippi have identified several sites where microorganisms have caused deterioration of the columns of concrete bridges embedded in soil (Trejo et al., 2008). Giannantonio et al. (2009), Magniont et al. (2011), Vollertsen et al. (2008), and Ghafoori and Mathis (1997) provide a list of microorganisms that can promote degradation in concrete in soils and waters. According to Bastidas-Arteaga et al. (2008), biodeterioration of concrete is mainly caused by bacteria, fungi, algae and lichens, and mussels (Perez et al., 2003). Once the pH of the surface of the concrete drops below 9 in the presence of sufficient nutrients, moisture, and oxygen, some species of sulfur bacteria, such as *Thiobacillus sp.*, can attach to the concrete surface and reproduce (Mori et al., 1992). As the pH continues to fall to moderate or weakly acidophilic conditions, *T. novellus*, *T. neapolitanus*, and *T. intermedius* establish on the surface of concrete (Milde et al., 1983). The type of bacteria is strongly dependent on the concrete pH and environmental conditions (Okabe et al., 2007).

Although no cases of microbiological degradation of concrete have been reported in nuclear applications, the degradation mode is considered credible, as below-grade environments may be conducive to microbe and bacteria growth. Thus, microbiological degradation of concrete structures exposed to groundwater or soil (below-grade) environments is considered credible, and therefore, aging management is required during the 60-year timeframe.

Concretes exposed to outdoor, sheltered, and fully encased (lined) environments

The outdoor and sheltered environments may provide favorable conditions for microbiological degradation mechanisms because of the potential presence of moisture. However, the conditions may be intermittent, and there is no evidence that actual concrete subcomponents in the DSS environment microbiologically degrade. In addition, fully encased concrete is considered to be largely protected from moisture intrusion. Thus, microbiological degradation of concretes exposed to outdoor, sheltered, and fully encased (lined) environments is not considered credible, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.13 Delayed ettringite formation

At the initial stage of fresh concrete curing, ettringite,[1] commonly referred to as "naturally occurring ettringite," is formed by the reaction of tricalcium aluminate and gypsum in the presence of water. The formation of naturally occurring ettringite in fresh concrete is not detrimental to the overall concrete performance. At the still-early stage of concrete curing, the naturally occurring ettringite may convert to monosulfoaluminate if curing temperatures are greater than about 70 degrees C [158 degrees F] (Fu, 1996). After concrete hardens, if the temperature decreases below this value, the monosulfoaluminate becomes unstable and, in the presence of sulfates released by the C-S-H gel, ettringite will reform. This mechanism is called "delayed ettringite formation" (DEF), which results in volume expansion and increased internal pressures in the concrete (Fu, 1996). Because the concrete has hardened at this stage, the volume expansion leads to cracking and spalling, with greatest severity commonly observed in below-ground structures with elevated temperatures from curing and heat of hydration (Shayan and Quick, 1992; Hobbs, 1999). DEF has been reported in precast concrete railroad ties in Sweden (Sahu and Thaulow, 2004), cast-in-place concrete structures in the southern United States after 10 years in service (Thomas et al., 2008), and mass concretes with high cement contents in the United Kingdom (Hobbs, 1999; Johansen and Thaulow, 1999). However, to date, no operating experiences exist of DEF degradation for concrete structures at nuclear power plants.

The conditions necessary for the occurrence of DEF are excessive temperatures during concrete placement and curing, the presence of internal sulfates, and a moist environment. ACI 318-05 (ACI, 2005) indicates that inspection reports shall document concrete temperature and protection during placement when the ambient temperature is above 35 degrees C [95 degrees F]. Protection measures during concrete placement include lowering the temperature of the batch water, cement, and aggregates as referenced in ACI 305R-10 (ACI, 2010). As such, following the ACI 318-05, ACI 305R-10, and ACI 308R-01 (ACI, 2008d) guidelines during concrete placement and curing can effectively limit the concrete temperature to below 70 degrees C [158 degrees F], therefore preventing the development of DEF. NUREG–1536 (NRC, 2010b) cites ACI 349 (ACI, 2007) and ACI 318 as applicable codes for the design and construction of concrete structures of the DSSs. In addition to the adequate placement and curing standards, no occurrences of DEF-related degradation of concrete have been reported in nuclear applications. Thus, DEF of concrete is not considered credible in

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[1] Ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) is the product of the reaction of gypsum and other sulfate compounds with calcium aluminate in the cement within the first few hours after mixing with water.

outdoor, sheltered, groundwater or soil (below-grade), and fully encased (lined) environments, and therefore, aging management is not required during the 60-year timeframe.

3.5.1.14 Salt scaling

Concretes exposed to outdoor environments and grounwater/soil (below-grade) environments above the freeze line

Salt scaling is defined as superficial damage caused by freezing a saline solution on the surface of a concrete body. The damage is progressive and consists of the removal of small chips or flakes of material. Similar to freeze and thaw damage, salt scaling takes place when concrete is exposed to freezing temperatures, moisture, and dissolved salts. The degradation is maximized at a moderate concentration of salt (e.g., from deicing salts), called the pessimum concentration (Marchand et al., 1999). Verbeck and Klieger (1957) reported that the pessimum concentration is independent of the types of salt species and is about 3 to 4 percent of the solute by weight. The most common deicing salts are sodium chloride and calcium chloride. Other deicing chemicals include magnesium chloride, urea, potassium chloride, ammonium sulfate, and ammonium nitrate.

Salt scaling of concrete roadways, pavements, sidewalks, driveways, decks, and other slabs is a common problem in locations exposed to cyclic freezing and thawing and deicing salts. For vertical surfaces, this damage mechanism is not expected to be operative unless the DSS concrete structure is surrounded by standing water containing salts. Therefore, this degradation mode is only expected to initiate and manifest in horizontal structures exposed to outdoor environments where water ponding can occur. Because salt scaling is closely related to freeze and thaw damage, the timeframe associated with the initiation of salt scaling of concrete could be relevant for both short- and long-term exposures. Thus, salt scaling damage is considered credible within the 60-year timeframe for DSS concrete structures exposed to outdoor and groundwater or soil (below-grade) environments above the freeze line, and therefore, aging management is required during the 60-year timeframe.

Concretes exposed to sheltered environments, fully encased (lined) in steel, and exposed to groundwater/soil (below-grade) environments under the freeze line

Concretes exposed to sheltered environments with low water availability or below-grade concrete maintained above freezing temperatures are not susceptible to salt scaling degradation. The heat load from the emplaced fuel in DSSs is expected to aid in drying the internal concrete surface, preventing the development of salt scaling inside the DSSs' concrete structure. Salt scaling damage is also expected to be insignificant for concretes fully encased by liners (e.g., metallic compartments)—even under freezing conditions—due to the lack of water and salt transfer between the concrete and the outside environment. Thus, interior DSS concrete surfaces, below-grade concretes maintained under the freeze line, and fully encased (lined) concrete not in direct contact with outdoor environments are not expected to undergo salt scaling damage within the 60-year timeframe, and therefore, aging management is not required.

3.5.2 Ceramic fiber insulation

The HI-STORM 100U underground system uses a divider shell to separate the intake cooling air from the heated air that streams up around the canister. This shell is insulated to minimize the preheating of the intake cooling air, with Kaowool® ceramic fiber insulation being a preferred insulation material in this DSS design.

3.5.2.1 Radiation damage

Neutron radiation has been shown to affect the strength and thermal diffusivity of ceramic fiber insulation. The effects will generally depend on the radiation dose, moisture content, temperature, and exposure period.

Snead et al. (1992) provide an example of the effects of neutron irradiation on ceramic-fiber interfacial strength. Results comparing unirradiated and 1-dpa neutron-irradiated ceramic fiber insulation samples (SiC/C/Nicalon) exhibited a marked decrease in both interfacial shear strength and frictional resistance to sliding. The decrease in interfacial shear strength resulted in the decrease of the ultimate strength of the ceramic fibers by about 25 percent. Similarly, the decrease in frictional resistance resulted in increased fiber toughness. The changes in the mechanical properties were attributed to the fiber shrinkage that causes a partial debonding of the fiber and matrix interface.

Other research provides examples of the effects of neutron irradiation on the thermal diffusivity of ceramic fiber insulation (Akiyoshi and Yano, 2008; Snead et al., 2000; Akiyoshi, 2009; Akiyoshi et al., 2006; Yano et al., 2000; and Snead et al., 2005). For example, Akiyoshi and Yano (2008) showed a degradation of thermal diffusivity in neutron-irradiated specimens by studying the macroscopic property changes in as-irradiated and annealed specimens under different temperatures from 373 to 766 degrees C [703 to 1,411 degrees F] and different neutron doses from 0.4 to 8.0×10^{22} n/cm^2 [2.6 to 51.6×10^{22} n/in^2]. The thermal diffusivity of as-irradiated specimens showed dependence on the neutron-irradiation dose and the irradiation temperature. Snead et al. (2000) have also demonstrated that the thermal conductivity of most ceramic fiber insulation materials undergoes a rapid reduction with irradiation when subjected to a fast-neutron fluence up to about 3.4×10^{21} n/cm^2 [2.2×10^{22} n/in^2] and irradiation temperature of about

200–700 degrees C [392–1,292 degrees F]. Gamma irradiation also results in a permanent decrease in the volume and surface resistivity of ceramic fibers at gamma values of around 1×10^9 rads [1×10^7 grays] (Davies, 1966). In general, the reduction of thermal diffusivity of ceramic fiber insulation should result in improved thermal insulation performance.

While the reduction of strength of ceramic fiber insulation due to radiation is not expected to compromise the SSC's intended function, a review of the radiation effects should be performed on a case-by-case basis.

The NRC reviewer should review the analyses contained in the applicant's original design-bases documents to determine whether the renewal application adequately addresses radiation damage of ceramic fiber insulation for an extended operating period of 60 years. This reexamination of the original analyses would typically be defined as TLAAs in the renewal application. The staff's guidance for the review of TLAAs is provided in NUREG–1927, Revision 1. If the original design basis does not include an analysis for an SSC that could reasonably be expected to be subject to radiation damage in the 60-year timeframe, the reviewer nevertheless should ensure that the application addresses this potential aging effect.

An applicant may conclude that an analysis cannot support a determination that fatigue will not challenge an important-to-safety function in the 60-year timeframe of the period of extended operation. In that case, the applicant may manage the aging of the associated SSC with an AMP.

3.5.2.2 Moisture absorption

Ceramic fiber insulation materials are generally porous (either open- or closed-pore network) and filled with atmospheric air in the dry condition. In nonencased SSCs, moisture transport through the insulation can be realized by diffusion and/or capillary suction. Vafai and Sarkar (1986) first modeled the transient heat and moisture transfer with condensation. The effect of condensates on the effective thermal conductivity and radiative heat transfer have also been considered in a transient model in porous media (Fan et al., 2000). This model suggests that the initial water content, service temperature, and insulation thickness are key factors influencing the insulation performance. Other parameters, such as the water vapor resistance, the thermal conductivity, and the insulation porosity were found to have smaller effects. The presence of moisture can significantly increase the insulation thermal conductivity (Cai et al., 2012).

The ceramic fiber insulation is foil faced or jacketed and therefore encased and protected from moisture. The high zinc content in the coating of the adjacent divider shell in the HI-STORM 100U system provides protection for the foil/jacket from galvanic corrosion. In addition, SCC of the foil/jacket is not a credible aging mechanism due to low stresses derived from the dead weight of the foil or jacket. Therefore, the integrity of the foil or jacket is not expected to be compromised, which will prevent moisture entering the ceramic fiber insulation. As such, moisture absorption of ceramic fiber insulation is not considered to be credible, and therefore, aging management is not required during the 60-year timeframe.

3.5.3 References

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3.6 Spent fuel assemblies

The SNF assembly components evaluated in this section include the zirconium-based cladding and fuel assembly hardware that provide structural support to ensure that the spent fuel is maintained in a known geometric configuration. The safety analyses for the ISFSI or DSS rely on the fuel assembly having a specific configuration (e.g., geometric form, a certain number of fuel rods or solid replacement filler rods in the assembly lattice). Although the spent fuel assembly is not an SSC of the ISFSI or DSS, depending on the particular design bases, the spent fuel must remain in its analyzed configuration during the period of extended operation for continuation of the approved design bases. Therefore, for these ISFSIs and DSSs, the condition of the SNF assembly and cladding are within the scope of renewal and are reviewed for aging mechanisms and effects that may lead to a change in the analyzed fuel configuration.

The experimental confirmatory basis that low-burnup fuel (≤45 gigawatt days per metric ton of uranium (GWd/MTU)) will remain in its analyzed configuration during the period of extended operation was provided in NUREG/CR-6745, “Dry Cask Storage Characterization Project—Phase 1; CASTOR V/21 Cask Opening and Examination” (Bare and Torgerson, 2001), and NUREG/CR-6831, “Examination of Spent PWR Fuel Rods after 15 Years in Dry Storage” (Einziger et al., 2003). This research demonstrated that low-burnup fuel cladding and other cask internals had no deleterious effects after 15 years of storage and confirmed the basis for the guidance on creep deformation and radial hydride reorientation in Interim Staff Guidance (ISG)-11, “Cladding Considerations for the Transportation and Storage of Spent Fuel, Revision 3” (NRC, 2003). In ISG-11, Revision 3, the NRC staff indicated that the spent fuel configuration is expected to be maintained as analyzed in the safety analyses for the ISFSI or DSS, provided certain acceptance criteria (regarding maximum fuel clad temperature and thermal cycling) are met and the fuel is stored in a dry inert atmosphere. The research results in NUREG/CR-6745 and NUREG/CR-6831 support a determination that degradation of low-burnup fuel cladding and assembly hardware should not result in changes to the approved design bases during the first period of extended operation, provided that the cask/canister internal environment is maintained. The U.S. Department of Energy (DOE) is expected to gather similar experimental confirmatory data to support the technical basis for storage of high-burnup (HBU) fuel during the first period of extended operation (EPRI, 2014).

The staff reviewed gap assessments for DSS, relevant technical literature, and operating experience from nuclear applications (NRC, 2014a; Chopra et al., 2014; Hanson et al., 2012; Sindelar et al., 2011; NWTRB, 2010) to identify potential degradation mechanisms in consideration of the materials and condition of the SNF at loading and the environment in dry storage. The SNF cladding materials are zirconium-based alloys. The primary components of the fuel assembly hardware are spacer grids, end fittings, guide tubes (PWR only), and assembly channels (BWR only). The materials of construction for these components include zirconium-based alloys, nickel alloys, and stainless steel. The staff’s assessement of the condition of the SNF assembly at loading considered changes to the fuel pellets and the zirconium-based cladding during reactor service, including hydrogen absorption by the cladding, swelling of the fuel pellets, increased rod pressurization due to helium and fission gas release, and pellet-cladding interactions. The storage environment is helium or an alternative cover gas in high radiation and temperature. A minimal amount of water (about 0.43 gram mole) is also considered to be retained inside the cask/canister (NRC, 2010). This moisture content is based on a design-basis drying process that evacuates the cask/canister to less than or equal to 3 torr [0.06 psi] and maintains a constant pressure for 30 minutes before closure.

The aging mechanisms considered for high burnup zirconium-based cladding (i.e., average assembly burnups exceeding 45 GWd/MTU) include hydride reorientation, delayed hydride cracking, thermal and athermal (low-temperature) creep and localized mechanical overload. These mechanisms are primarily driven by cladding hoop stresses, which are lower in low burnup fuel. The technical bases for these mechanisms (Sections 3.6.1.1–3.6.1.5) considered cladding hoop stresses for high burnup fuel, therefore these discussions are considered bounding to low burnup fuel. In addition, the demonstration program discussed in NUREG/CR-6745 (Bare and Torgerson, 2001) and NUREG/CR-6831 (Einziger et al., 2003) provided confirmation that hydride reorientation and creep will not compromise the configuration of low burnup fuel during the renewal period. Other aging mechanisms considered for both low and high burnup zirconium-based cladding include radiation embrittlement, fatigue, oxidation, pitting corrosion, galvanic corrosion, and SCC and MIC. Of these potential mechanisms, MIC was not considered to be applicable, as the aging mechanism is not expected to be operable under the inert atmosphere of dry storage. Detailed discussions regarding each of the potential aging mechanisms for zirconium-based cladding are provided in Section 3.6.1.

The degradation mechanisms considered for the assembly hardware include creep, fatigue, hydriding, general corrosion, SCC, and radiation embrittlement. Detailed discussions regarding each of these applicable aging mechanisms for assembly hardware are provided in Section 3.6.2.

3.6.1 Cladding materials

3.6.1.1 Hydride reorientation (high burnup fuel)

In reactor service, the zirconium-based fuel cladding absorbs hydrogen, which leads to the precipitation of hydride platelets as the dissolved hydrogen exceeds the solubility limit of the cladding. The primary source of the hydrogen is water-side corrosion (oxidation) of the cladding (Hanson et al., 2012; IAEA, 1993). The total concentration of hydrogen absorbed by the cladding (i.e., dissolved in the zirconium matrix and in precipitated hydrides) increases with burnup and varies axially across the fuel rods. For burnups above 45 GWd/MTU and up to 62 GWd/MTU (the current NRC licensing limit), the total hydrogen content for Zircaloy-2 is expected to be in the range of 260–300 weight parts per million [wppm] (NRC, 2015a; Geelhood and Luscher, 2014), 200–1,200 wppm for Zircaloy-4 (Mardon et al., 2010; Thomazet et al., 2005; King et al., 2002; Bossis et al., 2007; Hanson, 2016), ≤ 100 wppm for M5® (King et al., 2002; Bossis et al., 2007; Mardon et al., 2010; Thomazet et al., 2005, Billone, 2013, Hanson, 2016), and up to 550± 300 wppm for ZIRLO™ (Billone et al., 2013, Billone et al., 2015). When discharged from the reactor and during wet storage, the hydride platelets are mostly oriented in the circumferential-axial direction, with a smaller fraction oriented in the radial-axial direction.

Once the SNF assemblies are removed from wet storage and loaded into a DSS, the cask/canister cavity is vacuum dried and backfilled with an inert gas. During vacuum drying, the temperature of the SNF assemblies and the temperature-dependent solubility limit of hydrogen in the cladding will also increase. As a result, some of the hydrides present in the cladding will redissolve as hydrogen. The amount of dissolved hydrogen will depend on the peak cladding temperature during the vacuum drying operations, which, per ISG-11, Revision 3 (NRC, 2003), is not to exceed 400 degrees C [752 degrees F] for HBU fuel. For example, the maximum dissolved hydrogen at 400 degrees C [752 degrees F] is approximately 200 wppm based on representative solubility correlations (Kammenzind et al., 1996; Kearns et al., 1967). Once the loaded cask/canister is dried and backfilled, the cladding temperature will decrease over time, and upon a sufficient temperature drop (~65 degrees C [117 degrees F]), some of the hydrogen in solution will reprecipitate as new hydrides. During this process, the orientation of these precipitated hydrides may change from the circumferential-axial to the radial-axial direction. The degree of reorientation is primarily driven by the metallurgical microstructure of the cladding alloy and the cladding hoop stresses during drying operations and subsequent cooling, which are determined by the rod internal pressure at a given gas temperature.

Cladding with a high concentration of radial hydrides (determined by the DSS drying conditions) has been shown to have reduced ductility under pinch-load stresses at sufficiently low temperatures, thereby affecting the ability to retrieve the HBU fuel (Billone at al., 2013; Aomi et al., 2008). The degradation of the mechanical properties at a particular temperature (described as the "ductile-to-brittle transition temperature" or DBTT) depends on the interconnectivity and number density of radial hydrides (as determined by their length, distribution, and orientation), and the thickness of the outer-surface hydride rim. This phenomenon has led the staff to express concern about potential cladding failures when subjected to pinch-load stresses higher than the fuel's mechanical limit, if the cladding temperature decreases below the corresponding DBTT (NRC, 2015b). Therefore, as the cladding cools down during the 60-year timeframe, the extent of radial hydride reorientation and the DBTT are important for evaluating the cladding performance and ensuring that the HBU fuel remains in the analyzed configuration.

The primary driving force for radial hydride reorientation is the cladding hoop stresses, which are determined by the peak cladding temperature during drying operations. A review indicates that there is no consensus in the literature on minimum level or threshold hoop stresses needed to reorient hydrides for a given cladding alloy and temperature, as discussed in the following references:

- *Zircaloy-4:* Data from Chung (2004), Daum et al. (2006), and Chu et al. (2008) suggest that the threshold hoop stress for hydride reorientation in Zircaloy-4 is about 90 MPa [13 ksi] for peak temperatures at or near 400 degrees C [752 degrees F] for both irradiated and unirradiated rods. Other data obtained from irradiated cladding (Einziger and Kohli, 1984; Cappelaere, et al., 2001; and Goll, et al., 2001) suggest that hoop stresses greater than 120 MPa [17 ksi] may be required. Most recently, Kim et al (2015a) showed threshold stresses for hydride reorientation in unirradiated Zircaloy-4 of 60 ± 5 MPa [8.7 ± 0.7 ksi] at 400 degrees C [752 degrees F], 68 ± 5 MPa [9.8 ± 0.7 ksi] at 335 degrees C [635 degrees F], 75 ± 6 MPa [10.9 ± 0.9 ksi] at 300 degrees C [572 degrees F], and 90 ± 6 MPa [13.0 ± 0.9 ksi] at 235 degrees C [455 degrees F]. Kamimura (2010) also reported a threshold stress for Zircaloy-4 of about 100 MPa [16 ksi] at 275 degrees C [527 degrees F] for a nominal burnup of 48 GWd/MTU.

- *Zircaloy-2:* Kamimura (2010) reported a threshold hoop stress of 70 MPa [10 ksi] for Zircaloy-2 (no zirconium liner) of nominal burnup of 40 GWd/MTU at 200 degrees C [392 degrees F], and 70 MPa [10 ksi] for Zircaloy-2 (with zirconium liner) of nominal 50 GWd/MTU and 55 GWd/MTU burnups at 300 degrees C [572 degrees F].

- *Advanced alloys:* Kamimura (2010) reported a threshold stress of 90 MPa [13 ksi] for ZIRLO™ at 250 degrees C [482 degrees F] for a nominal burnup of 55 GWd/MTU. Billone et al. (2013) reported reorientation of M5® cladding at their lowest studied hoop stress of 90 MPa [16 ksi] for a peak cladding temperature of 400 degrees C [752 degrees F] and nominal burnup of 68 GWd/MTU.

These threshold hoop stresses for hydride reorientation were compared to estimated hoop stresses for representative BWR and PWR fuel assemblies. Raynaud and Einziger (2015) estimated the hoop stresses for 10 × 10 BWR and 17 × 17 PWR fuel assemblies as a function of decay gas release and fuel pellet swelling, which accounted for decay gas released to the pellet-clad gap. The maximum calculated hoop stress during drying operations for the BWR cladding was approximately 40 MPa [5.8 ksi] at a peak cladding temperature close to 400 degrees C [752 degrees F]. Similarly, the maximum calculated hoop stress during drying operations for PWR cladding was approximately 100 MPa [14.5 ksi] at 400 degrees C [752 degrees F], which rapidly decays and falls well below 50 MPa after a few decades in dry storage. These calculations did not account for ZIRLO™-clad integral fuel burnable absorber (IFBA) rods with hollow and solid blanket pellets; however, these rods are expected to experience higher maximum hoop stresses (Bratton et. al, 2015). Since the calculated hoop stresses exceed the experimental values in the literature for when radial hydride reorientation was observed, the staff considers that the radial hydride precipitation is credible in both in BWR and PWR fuel claddings in dry storage.

The cladding alloy and corresponding fabrication process are also important factors for defining the extent of hydride reorientation. Two predominant cladding microstructures are produced during fabrication: (1) recrystallized annealed (RXA) and (2) cold worked stress relieved (CWSR) annealed. Zircaloy-4 (PWR) and ZIRLO™ (PWR) are generally CWSR, whereas Zircaloy-2 and M5® are RXA. Because hydrides tend to precipitate in the grain boundaries, RXA claddings are more susceptible to hydride reorientation, since these cladding types have a larger fraction of grain boundaries in the radial direction (equiaxed grains) relative to CWSR claddings (which have more elongated grains).

The staff also considered the effect of the cladding cooling rate on the degree of hydride reorientation. The cooling rate post-drying and under dry storage is expected to be in the range of 10^{-3} to 10^{-5} degrees C/hr [1.8×10^{-3} to 1.8×10^{-5} degrees F/hr]. Most of the experimental studies reported in the literature have used cooling rates in the range of 0.6–30 degrees C/hr [1.08–54 degrees F/hr] (Aomi et al., 2008). However, an analysis of ductility data collected at different cooling rates in Aomi et al. does not show a clear trend. Chan (1996) also developed a micromechanical model to determine the effect of slow cooling rates on hydride reorientation and morphology, including volume fraction of both radial and circumferential hydrides and continuity of the hydride network. Using experimental data to validate the model, Chan concluded that the cooling rate exerts no direct influence on radial hydride precipitation; instead, hydride orientation is dictated by the cladding stresses during hydride precipitation, regardless of the cooling rate. Therefore, the staff concludes that the slow cooling rates experienced post-drying and during dry storage are not expected to inhibit the precipitation of radial hydrides.

Available DBTT data on HBU fuel cladding samples with radial hydrides have been obtained under conservative conditions and acceptance criteria (e.g. testing was performed on defueled samples, which do not account for the composite pellet-clad mechanical behavior) (Fuketa et al., 2003; Billone et al., 2013; Aomi et al., 2008). For example, Billone et al. showed that Zircaloy-4, ZIRLO™, and M5® cladding samples subjected to a radial hydride reorientation treatment exhibited lower ductility under pinch-load stresses at low relative temperatures (less than 200 degrees C [392 degrees F]). The radial hydride treatment was designed to simulate drying and storage conditions (i.e., peak cladding temperature of 400 degrees C [752 degrees F] and peak hoop stresses of ~110 MPa [16.0 ksi] and ~140 MPa [20.3 ksi]). General conclusions from Billone et al. were that: (1) the DBTT generally increases with increasing hoop stresses (i.e., the degradation of cladding mechanical properties shifts to higher cladding temperature), (2) both the susceptibility to radial hydride precipitation and degradation of mechanical properties depend on cladding type and initial hydrogen content, and (3) depending on the cladding and test conditions, the DBTT can occur at temperatures in the range of approximately 20 degrees C to 185 degrees C [68 to 328 degrees F]. The results for as-irradiated Zircaloy-4 are consistent with studies by Wisner and Adamson (1998) and Bai et al. (1994).

Considering the hydrogen content, peak drying temperatures, and corresponding hoop stresses, the staff concludes that hydride reorientation in zirconium-based HBU cladding is credible during the 60-year timeframe. Further, depending on the specific fuel contents, it is possible for some of the cladding to reach temperatures near or below the DBTTs reported in the literature. Therefore, degradation of mechanical properties during pinch-type stresses due to hydride reorientation is considered a credible aging mechanism for HBU fuel claddings.

The degradation of mechanical properties due to hydride reorientation is only expected to potentially compromise the ability to maintain the analyzed fuel configuration during pinch-type loads. These loads are only expected during fuel retrieval operations, if the design bases of the DSS or ISFSI rely on retrievabilty of the HBU fuel on a single-assembly basis. Pinch-type loads are not expected to be present during normal, off-normal, and accident conditions of storage. More specifically, the tensile stress field associated with potential inertial rod bending during storage is expected to be parallel to both radial and circumferential hydrides and not expected to compromise the structural integrity of the cladding. The NRC is sponsoring confirmatory research to this effect at Oak Ridge National Laboratory, and the results will be publicly-available soon (see Wang and Wang (2015) for details on the experimental protocol).

Until the Oak Ridge data is publicly-available, the staff has proposed two alternatives for demonstrating that the safety analyses pertaining to the analyzed spent fuel configuration will not be compromised by the effects of hydride reorientation. The first approach relies on the applicant performing a defense-in-depth analysis, assuming credible reconfiguration based on 1 percent fuel failure for normal conditions of storage, 10 percent failure for off-normal conditions of storage, and 100 percent or other justifiable value for accident conditions. The staff has issued a generic consequence analysis for both vertical and horizontal storage configurations in NUREG/CR-7203 (Scaglione et al., 2015), which can be used by applicants in the development of their defense-in-depth analysis. A second approach relies on the evaluation of data from a demonstration (surrogate) program consistent with the guidance in Appendix D of NUREG–1927, Revision 1 (NRC, 2016). For example, destructive examination from the DOE/EPRI cask demonstration project (EPRI, 2014) may be used as confirmation that hydride reorientation has not compromised the ability to retrieve the spent fuel on a single-assembly basis. An example AMP consistent with the guidance in Appendix D of NUREG–1927, Revision 1 is provided in Chapter 5.

3.6.1.2 Delayed hydride cracking (high burnup fuel)

Delayed hydride cracking (DHC) is a time-dependent mechanism traditionally thought to occur by the diffusion of hydrogen to an incipient crack tip (notch, flaw) in the cladding, followed by nucleation, growth, and subsequent fracture of the precipitated hydrides at the crack tip (Hanson et al., 2012). Hydrogen dissolved in the cladding (see Section 3.6.1.1) can diffuse up a stress gradient in the crystalline lattice, or into the stress field at the core of an edge dislocation (Cox, 1997). The concentration gradient established by the stress gradient may lead to hydrogen supersaturation (i.e., solubility limit being exceeded) leading to the precipitation of hydrides at the crack tip. The precipitated hydride will continue to grow by the dissolution of hydrides in the low-stress regions of the material and by the continued diffusion of hydrogen up the stress gradient. Once the hydride reaches a critical size, it will crack and propagate to the end of the hydride, where it will blunt. The cycle could then repeat, until the crack propagates through the thickness of the material. DHC of spent fuel cladding has been studied under thermal transients representative of reactor operation (Kubo, 2012; Kim, 2009b) and representative of dry storage (Sasahara and Matsumura, 2008; EPRI, 2002).

Requisite conditions for DHC are the presence of: (i) hydrides, (ii) existing crack tips (notch, flaws) that act as initiating sites, and (iii) sufficient cladding hoop stresses. Regarding requisite hydrides, a threshold for crack initiation cannot be readily defined. Simpson and Ells (1974) observed DHC with hydrogen concentration as little as 10 ppm in Zr-2.5 percent Nb cladding, although testing was performed at room temperature (i.e., a much lower temperature than those expected during the renewal period). Similarly, Coleman et al. (2009) were able to induce DHC in Zircaloy-4 at 200 wppm of hydrogen. Regarding requisite existing (incipient) crack tips, EPRI (2002) estimated the maximum initial depth of existing crack tips to be 140 µm [5.5 mils] or approximately 28 percent of the remaining wall of a typical 17 × 17 PWR cladding with 600 µm [23.6 mils] of original cladding thickness, and 100 µm [4 mils] of oxidation during its exposure in the reactor. Conversely, Raynaud and Einziger (2015) estimated the maximum initial depth of existing crack tips to be 120 µm [4.7 mils] for a cladding oxide thickness of 100 µm [4 mils]. Regarding requisite hoop stresses for crack initiation, the mechanism requires that the stress intensity factor at the crack tip exceed a threshold value, denoted as K_{IH}.

Most DHC studies have been performed under thermal transients representative of reactor operation, primarily on CANDU pressure tubes (Zr–2.5 percent Nb) and Zircaloy-2 cladding. Chan (2013) conducted an extensive literature review of experimentally determined K_{IH} values for DHC crack initiation. In that review, K_{IH} values for Zircaloy-2 are in the range of 5–14 MPa√m [4.55–12.74 ksi√in] at 25–300 degrees C [77–572 degrees F], and in the range of 5–10 MPa√m [4.55–9.10 ksi√in] for Zr-2.5 percent Nb cladding at 75–300 degrees C [167–572 degrees F] (Chan, 2013, Figures 2 and 3). Kubo et al. (2012) also compiled K_{IH} values for Zircaloy-2 in the range of 3–13 MPa√m [2.73–11.8 ksi√in]. Kim (2009a) also measured a K_{IH} value of 2.5 MPa√m [2.28 ksi√in] for Zr-2.5 Nb cladding at 160 degrees C [320 degrees F]. Based on the available data, the staff considered a reference K_{IH} value of 5.0 MPa√m [2.73 ksi√in] to be reasonable for determining the potential for DHC initiation.

Raynaud and Einziger (2015) estimated the cladding hoop stresses while conservatively accounting for release of fission gases and decay gases during storage, including stresses due to radiation-induced pellet swelling during storage. Raynaud and Einziger concluded that DHC cannot occur for a K_{IH} of 5 MPa√m [4.55 ksi√in], because the flaw size needed to induce DHC is much larger than the initial depth of potential existing cracks (120 µm [4.7 mils]). The estimated critical flaw size needed to initiate DHC in BWR fuel cladding is larger than 50 percent of the cladding thickness for 300 years of dry storage. For PWR cladding, the critical flaw size is larger than 30 percent of the cladding thickness for the first 5 years of the dry storage and larger than 50 percent of the cladding thickness beyond the first 5 years up to 300 years of dry storage. The calculations in Raynaud and Einziger did not account for the hoop stresses in ZIRLO™-clad IFBA rods with hollow and solid blanket pellets, which are expected to be higher than standard rods (Bratton et al., 2015). Therefore, the staff performed similar calculations to those in Raynaud and Einziger for IFBA rods, assuming a K_{IH} value of 5 MPa√m [2.73 ksi√in] and a conservative IFBA-rod hoop stress of 130 MPa [21.75 ksi]. These calculations show that the critical flaw size for the PWR cladding is still larger than 30 percent of the cladding thickness for the first 5 years of dry storage and larger than approximately 45 percent of the cladding thickness beyond the first 5 years up to 300 years of dry storage. Therefore, the staff concludes that the critical flaw size needed to induce DHC, in both standard and IFBA rods, is much larger than the initial depth of potentially existing cracks (120 µm [4.7 mils]). The staff considers that the hoop stress value assumed for IFBA rods is adequately conservative for this calculation, since a limited (less than 1 percent) population of the rods is expected to experience these pressures (Bratton et al., 2015). In addition, most design-bases peak cladding temperatures are well below the limit defined in ISG-11, Revision 3 (i.e., 400 degrees C [752 degrees F]), which would considerably decrease the cladding hoop stresses. Therefore, the assumptions and analyses discussed above are considered reasonably bounding and indicate that DHC is not a credible aging mechanism during the 60-year timeframe.

The staff also considered a DHC model proposed by Kim et al. (2008, 2009b), which evaluated cladding absent thermal cycling, where multiple parameters including creep deformation, cladding burnup, solvus hysteresis, and the δ-to-γ hydride phase transition were analyzed. This model, still under review by the international DHC research community (NRC, 2014a), suggests that K_{IH} may be reduced (i) upon cooling below 180 degrees C [356 degrees F] (due to a hydride phase transformation from the γ to δ phase) and (ii) if there are sufficient stresses and stress risers in the rod (e.g., residual stresses at the end cap weld region, incipient cracks due to fuel-cladding interaction). Thermal gradients may also affect the kinetics of hydride precipitation. The staff reviewed this study, in light of the assumptions made in the previous discussion. However, Kim does not quantify K_{IH} values; therefore, adequate conclusions cannot be made with respect to threshold stresses. The NRC (2014a) and Hanson et al, (2012) summarized Kim's work and proposed additional research for confirmation.

Finally, the staff considered the contribution of cladding stresses due to pellet-clad bonding and its potential to facilitate DHC initiation (Wang, 2014a,b). The previously-discussed Raynaud and Einziger (2015) study did not account for potential stress concentration effects due to pellet-pellet interfaces and pellet fragment-to-fragment friction forces that could result in more severe pellet-to-cladding mechanical interaction (PCMI) than for a perfectly cylindrical pellet (as assumed in the paper). Recently, Ahn et al. (2013) estimated stress concentrations from pellet-clad mechanical stresses due to the radiation-induced pellet swelling up to 100 years, independent of hoop stresses due to continued fission and decay gas release. The work estimated that, for HBU fuel, the average pellet-swelling-induced PCMI stress concentration was on the order of 200 MPa [29 ksi] locally.[1] Literature indicates that radiation-induced pellet swelling is expected reach its maximum value beyond the 60-year timeframe (Rondinella et al., 2010a,b; 2012). Therefore, the staff does not have evidence that the potential for high PCMI stress concentrations due to radiation-induced pellet swelling would facilitate DHC crack initiation until past the first renewal period.

Based on the above analyses and discussion, the staff concludes that delayed hydride cracking of the zirconium-based cladding is not credible during the 60-year timeframe and therefore, aging management is not required.

3.6.1.3 Thermal creep (high burnup fuel)

Creep is the time-dependent deformation of a material under stress. Creep in zirconium-based cladding is caused by the hoop stresses from the rod internal pressure at a given fuel temperature. Therefore, the mechanism is expected to be self-limiting, due to the decreasing temperatures and creep-induced volume expansion, which results in lower internal rod

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[1] For low-burnup fuel, pellet expansion stresses will be minimal, because the gap between the cladding and the pellet will accommodate the swelling.

pressures with time. Excessive creep of the cladding during dry storage could lead to thinning, hairline cracks, or gross ruptures (Hanson et al., 2012), which may affect the ability to safely retrieve the HBU fuel on a single-assembly basis (if required by the design bases).

The main driving force for cladding creep at a given temperature is the hoop stress caused by internal rod pressure, which accounts for the fission and decay gases released to the interspace between the fuel and cladding. Fuel pellet swelling also may result in localized stresses due to the mechanical interaction between the cladding and the fuel. Pellet swelling may occur due to (i) the incorporation of soluble and insoluble solid fission products in the fuel matrix, (ii) the formation of intra- and intergranular fission gas bubbles, particularly in the hot interior region of a fuel pellet, and (iii) the formation of a large number of small gas bubbles in the fine-grained ceramic structure that builds inward from the outer pellet surface for HBU fuel.

Raynaud and Einziger (2015) estimated the transient cladding hoop stresses during dry storage for typical 10 × 10 BWR and 17 × 17 PWR fuel assemblies. These estimates accounted for a credible release of fission and decay gases to the fuel-cladding interspace, pellet swelling, and fuel and cladding temperature decay with time. The study reported peak cladding hoop stresses less than 50 MPa [7.25 ksi] for BWR and less than 100 MPa [14.5 ksi] for PWR fuel assemblies. Raynaud and Einziger used these hoop stress estimates to calculate cumulative cladding strains for the representative assemblies over a 60-year period of dry storage. The authors reported a maximum cladding strain of 0.54 percent for the representative 10 × 10 BWR fuel cladding and 1.04 percent for the representative 17 × 17 PWR fuel cladding. However, these calculations did not account for the hoop stresses in ZIRLO™-clad IFBA rods with hollow and solid blanket pellets, which are expected to be higher than those for standard rods (Bratton et al., 2015). Therefore, the staff performed calculations to estimate the cladding strain for IFBA rods using the Raynaud and Einziger approach. Using a conservatively bounding hoop stress of 150 MPa [21.75 ksi], the maximum cladding strain was estimated to be near 2.1 percent. The elastic strain limit for various zirconium-based cladding alloys with circumferential hydrides is less than 1 percent (Geelhood et al., 2008) and is expected to be lower for cladding containing both circumferential and radial hydrides. Therefore, the staff concludes that the cladding in both standard and IFBA fuel rods is expected to undergo creep strains during the 60-year timeframe.

The staff has discussed the potential for creep deformation in ISG-11, Revision 3 (NRC, 2003), which includes acceptance criteria (regarding maximum fuel clad temperature during dry storage operations and adequate thermal cycling limits) to provide reasonable assurance that the spent fuel assemblies will remain in the configuration analyzed in the approved design bases. The references cited in ISG-11, Revision 3, provide experimental evidence that cladding failures are not expected for creep strains below 2 percent. These references provide support that gross ruptures of the cladding are unlikely due to creep during dry storage, because the creep-induced strain is expected to be near or less than 2 percent for the majority of the cladding alloys and close to 2 percent for the ZIRLO™-clad IFBA rods. For example, no failures were observed for creep strains below 2 percent strain for in-creep tests at temperatures between 250 and 400 degrees C [482 and 752 degrees F] for Zircaloy cladding irradiated up to burnup of 64 GWd/MTU (Spilker et al., 1997; Goll et al., 2001; EPRI, 2002). In addition, Bouffioux and Rupa (1998) conducted various cladding creep tests with unirradiated, prehydrided, stress-relief annealed low-Sn Zircaloy-4 PWR cladding tubes, with hydrogen levels in the range of 100–1,100 wppm. The authors observed gross ruptures of the cladding only after creep strains exceeding 8 percent. Tsai and Billone (2003) also tested irradiated stress-relief annealed Zircaloy-4 with varying levels of hydrogen levels at various temperature and hoop stresses, which did not reveal cladding failures at a strain of 5.83 percent. More recent data on optimized ZIRLO™ by Pan et al. (2013) also indicate a plastic strain range in the same range as Zircaloy.

The staff concludes that thermal creep of zirconium-based cladding is credible during the 60-year timeframe. However, due to the high creep capacity of zirconium-based alloys, thermal creep is not expected to result in cladding failures and reconfiguration of the fuel, if the approved design bases are consistent with the acceptance criteria in ISG-11, Revision 3. The staff recognizes that the experimental evidence used in support of ISG-11, Revision 3, is based on short-term testing. Therefore, the staff issued guidance in Appendix D of NUREG–1927, Revision 1 (NRC, 2016) for the use of a demonstration program to confirm these expected fuel conditions after a substantial storage period (~10 years). The program would provide confirmation for accelerated cladding creep testing used as basis for the guidance recommendation for the maximum temperature in ISG-11 (NRC, 2003), and that sufficient creep capacity exists for the renewal period. For example, non-destructive and destructive examination from the DOE/EPRI cask demonstration project (EPRI, 2014) may be used as confirmation that the design-basis fuel remains in the analyzed configuration and that sufficient creep margin exists for the first renewal period. An example AMP consistent with the guidance in Appendix D of NUREG–1927, Revision 1 is provided in Chapter 5.

3.6.1.4 Low-temperature creep (high burnup fuel)

Low-temperature creep (also called “athermal creep”) may occur when sustained hoop stresses operate on the cladding material at or near ambient temperature (NRC, 2014a). Various athermal creep mechanisms have been proposed at low stresses (e.g., Nabarro-Herring, Coble, and Harper-Dorn creep mechanisms) (Murty, 2000), although there is no evidence or literature information to support that these will be operational on zirconium-based alloys. However, the literature shows that low-temperature creep has been shown to occur in titanium and its alloys, which leads to deformation twinning (Jaworski and Ankem, 2006). Since both titanium and zirconium have the same crystalline structure (hexagonal close packed crystalline), the zirconium-based cladding was reviewed for its susceptibility to low-temperature creep.

In materials such as α and α-β titanium alloys, which are comparable to the zirconium-based alloys used for fuel cladding, low-temperature creep has been observed when tensile stresses exceed 25 percent of the yield strength (Ankem and Wilt, 2006). For example, Ankem and Wilt reported a threshold stress in the range of 25–50 percent of the yield stress for Ti Grade 7, and 35–60 percent of the yield stress for Ti Grade 24. The yield strength of the irradiated zirconium-based cladding at low temperatures (550–1,000 MPa [79.8–145 ksi]; Geelhood et al, 2008; Forgeaud, et al., 2009; Cazalis et al., 2005) is expected to be close to the yield strength of Ti Grade 24 (825 MPa [119.6 ksi]) and well above the yield strength of Ti Grade 7 (275 MPa [39.9 ksi]) (Ibarra et al., 2007). Therefore, the staff considered the results in Ankem and Wilt to provide reasonable acceptance criteria for determining if low-temperature creep is a credible aging mechanism in the 60-year time frame.

The main sources of sustained hoop stresses at low temperatures are expected to be the rod internal pressure and pellet-cladding mechanical interaction. Raynaud and Einziger (2015) estimated the cladding hoop stresses after 300 years of storage to be approximately 25 MPa [3.62 ksi] and 35 MPa [5.07 ksi] for representative BWR and PWR fuel cladding, respectively. These estimates accounted for a credible release of fission and decay gases to the fuel-cladding interspace, pellet swelling, and fuel and cladding temperature. The hoop stresses for IFBA rods are conservatively expected to be around or less than 75 MPa [10.87 ksi] (Bratton et al., 2015). These hoop stress estimates are all less than 25 percent of the yield strength of zirconium-based cladding (i.e., below the expected range of 550–1,000 MPa [79.8–145 ksi] near ambient temperature for cladding with circumferential hydrides only (Geelhood et al., 2008; Fourgeaud, et al. 2015; Cazalis et al., 2005)). Further, more recent data (Kim et al., 2015a, 2015b) suggest that, even with the potential decrease in yield strength due to radial hydrides (which conservatively does not account for a potential increase in yield strength due to irradiation), the hoop stresses in the cladding are still maintained below 25 percent of the yield strength of irradiated cladding with both circumferential and radial hydrides.

Raynaud and Einziger acknowledged that the low-temperature creep models are not programmed into FRAPCON-DATING, which the authors used to predict the elevated temperature cladding creep (see Section 3.6.1.3). The authors noted that extrapolations of the high-temperature cladding creep model results in immeasurably small values of cladding strains at low temperature. However, the lack of cladding creep beyond 50 years (corresponding to temperatures below approximately 200 degrees C [392 degrees F]) results in smaller strains being predicted in these calculations. Therefore, the calculated cladding hoop stresses are conservative when compared to the 25-percent criteria, as athermal creep-induced strains would reduce these stresses.

The staff further considered the contribution of cladding stresses due to pellet-clad bonding and its potential to facilitate athermal creep. The previously discussed Raynaud and Einziger study did not account for potential stress concentration effects due to pellet-pellet interfaces and pellet fragment-to-fragment friction forces that could result in more severe PCMI than for a perfectly cylindrical pellet (as assumed in the paper). Recently, Ahn et al. (2013) estimated stress concentrations from pellet-clad mechanical stresses caused by the radiation-induced pellet swelling up to 100 years, independent of hoop stresses due to fission and decay gas release. The work estimated that, for HBU fuel, the average pellet-swelling-induced PCMI stress concentration was on the order of 200 MPa [29 ksi] locally. Literature indicates that radiation-induced pellet swelling is expected to reach its maximum value beyond the 60-year timeframe (Rondinella et al., 2010a,b; 2012). Therefore, PCMI stress concentrations due to radiation-induced pellet swelling are not expected to exceed a threshold stress of 25 percent of the yield stress (similar to the titanium data in Ankem and Wilt, 2006) during the 60-year timeframe.

In summary, literature on the creep strain and creep rate of the zirconium-based cladding materials at room temperature per the hoop stresses expected during extended storage is not available. Therefore, it is not possible to directly assess the low-temperature creep of the zirconium-based cladding materials. However, the staff has reviewed the threshold levels of tensile stresses for low-temperature creep in the similar crystalline-structured (hexagonal close packed crystalline) materials, which indicate that cladding hoop stresses on the cladding must exceed approximately 25 percent of yield strength for athermal creep to be credible. The room temperature hoop stresses on the zirconium-based cladding are expected to be less than 25 percent of the yield strength. Therefore, the low-temperature (athermal) creep mechanism is not considered credible, even for the unlikely scenario where fuel reaches room temperature during the 60-year timeframe. Therefore aging management is not required during the 60-year timeframe.

3.6.1.5 Mechanical overload (high burnup fuel)

Mechanical overload is generally associated with PCMI, which could compromise the cladding integrity during storage. PCMI is likely during reactor operations when the reactivity transient during a reactivity-initiated accident (RIA) results in a rapid increase in a fuel rod power, leading to a nearly adiabatic heating of the fuel pellets and potential failure of the fuel cladding. In either commercial BWRs or PWRs, cladding failures have not been attributed to PCMI. However, data generated in experimental reactors conducting ramp testing of heavily hydrided fuel claddings indicate that hydride rims with large hydride number density at the cladding outer surface may lead to crack initiation (Adamson et al., 2006). The cracks could propagate from the outside toward the inner cladding surface, potentially resulting in failures.

During dry storage, PCMI stresses could develop due to pellet swelling and release of fission gases to the gap between the fuel and cladding. PCMI could lead to the opening of existing flaws in the cladding, potentially resulting in the release of fission gases and other fission products into the cask environment. The existing flaws in undamaged fuel are likely to be of any of the following: (i) surface (nonthrough-wall) cracks on the inner or outer wall, (ii) hairline cracks, (iii) wall thinning due to oxide spallation on the outer surface, or (iv) wall thinning due to fretting wear on the outer surface (NRC, 2014a).

Jernkvist et al. (2004) developed a criterion to determine the likelihood of PCMI during RIA, which relies on estimating a threshold strain as a function of temperature, strain rate, hydrogen concentration in cladding, and neutron fluence. However, this criterion is only applicable when the cladding temperature is increasing, making it inapplicable to dry storage, where temperatures decrease with time, barring any fluctuations from changes in ambient temperature.

A method previously used to characterize PCMI failures in the cladding involves measuring the creep strain capacity at a given creep strain rate (Jernkvist et al., 2004). More specifically, PCMI-induced failures are observed when the cladding strain at a given strain rate exceeds a threshold (Jernkvist et al., 2004; Fuketa et al., 2003). The threshold strain is a function of cladding temperature, irradiation, and hydrogen concentration. PCMI-induced failures have been reported at cladding strains exceeding 1 percent for strain rates in the range of 10^{-5} to 10^{-3} s^{-1} at room temperature for various levels of hydrogen concentration (Jernkvist et al., 2004). At higher temperatures, the strain at failure is above 6 percent between 523 and 673 K [482 to 752 degrees F] for strain rates in the range of 10^{-5} to 10^{-3} s^{-1} (Jernkvist et al., 2004). This threshold strain at higher temperature is applicable for cladding hydrogen content up to 1,200 wppm. These results are consistent with those by Fuketa et al. (2003), which exhibited similar threshold strains between 373 and 573 K [212 to 572 degrees F] with hydrogen concentrations up to 1,450 wppm. These results can be compared with data discussed in Section 3.6.1.3, which show that, for comparable strain rates in the order of 10^{-4} s^{-1} to 10^{-5} s^{-1}, no failures were observed for creep strains below 2 percent for in-creep tests at temperatures between 150 and 400 degrees C [423 and 752 degrees F] for Zircaloy cladding irradiated up to burnup of 64 GWd/MtU (Spilker et al., 1997; Goll et al., 2001; EPRI, 2002).

The staff reviewed the aforementioned creep strain and strain rate threshold criteria against the results in Raynaud and Einziger (2015), which estimated the temperature-dependent hoop stresses on the cladding while accounting for credible release of fission and decay gases and pellet swelling. The authors estimated maximum cladding strains of 0.54 percent for the 10 × 10 BWR fuel cladding and 1.04 percent for the 17 × 17 PWR fuel cladding at a strain rate of 10^{-10} s^{-1} expected during dry storage. The authors stated that all of the cladding strain is expected to occur during the first 50 years of storage. These calculations did not account for the hoop stresses in ZIRLO™-clad IFBA rods with hollow and solid blanket pellets, which are expected to be higher than standard rods (Bratton et al., 2015). The staff performed calculations to estimate the cladding strain for IFBA rods using the Raynaud and Einziger approach. Using a conservatively bounding hoop stress of 150 MPa [21.75 ksi], the maximum cladding strain was estimated to be near 2.1 percent for IFBA rods. These values indicate sufficient strain capacity per the previously discussed creep strain and strain rate threshold criteria (Jernkvist et al., 2004; Fuketa et al., 2003), which is considered conservatively bounding as the strain rates in dry storage are expected to be approximately five to seven orders of magnitude lower than 10^{-5} to 10^{-3} s^{-1}. Therefore, the staff concludes that cladding failures due to PCMI-induced mechanical overload are not considered credible during the 60-year timeframe, and aging management is not required.

3.6.1.6 Oxidation

In the presence of residual amounts of water and high enough temperature, zirconium-based cladding can be oxidized according to the following chemical reaction: $Zr + 2H_2O = ZrO_2 + 2H_2$ (Jung et al., 2013; Cox, 1976, 1988; Rothman, 1984).

Jung et al. (2013) conducted various scoping calculations to determine the extent of cladding oxidation during dry storage in the presence of up to 1 L [0.26 gal] (equivalent to 55.5 moles) of residual water. The amount of residual water considered is significantly higher than the residual water amount of 0.43 moles expected after vacuum drying, as per NUREG–1536 (NRC, 2010). The scoping calculations were based on a representative storage system loaded with the equivalent of 21 Babcock & Wilcox SNF assemblies, each containing 208 fuel rods in a storage canister. Jung et al. discussed temperature-dependent cladding oxidation kinetics for both Zircaloy-2 and Zircaloy-4, concluding that the maximum cladding thickness loss due to oxidation is not expected to exceed 10 μm [0.4 mils], even with complete consumption of the assumed 1 L [0.26 gal] of residual water. The loss of cladding thickness due to oxidation represents less than 2 percent of the original cladding thickness. Therefore, cladding oxidation is considered to be insignificant, and aging management is not required during the 60-year timeframe.

3.6.1.7 Pitting corrosion

Pitting corrosion initiates and propagates when (i) there is an aggressive chemical environment that results in corrosion potential being greater than the repassivation potential and (ii) there is enough cathodic capacity to sustain the propagation of the pitting corrosion (Shukla et al., 2008). Zirconium is a passive material and is protected by a ZrO_2 surface film (Palit and Gadiyar, 1987). The surface oxide readily reforms if broken, but zirconium is not completely immune to pitting. Halides (i.e., anions of fluorine, chlorine, bromine, and iodine) in aqueous or gaseous forms could initiate pitting. For example, pitting of zirconium has been shown to occur in hydrochloric acid solutions containing ferric (Fe^{3+}) or cupric (Cu^{2+}) ions (Palit and Gadiyar, 1987).

Inside the cask's or canister's internal environment, a limited amount of residual water is expected to be retained following drying, which will be in the liquid state once temperatures are near or below 100 degrees C [212 degrees F]. The residual water amount is expected to be less than 1 mole per NUREG–1536 (NRC, 2010). During storage, most residual water is expected to decompose into hydrogen and oxidizing species, such as oxygen and hydrogen peroxide, with time (Jung et al., 2013). It is possible for trace amounts of water to remain in the vapor phase but is not expected to be in the liquid phase during dry storage, due to the low relative humidity in the cask or canister cavity. For example, the relative humidity inside a cavity volume of 2.1 m^3 [554.8 gal], assuming a residual water content of 0.43 mole [per NUREG–1536] at 25 degrees C [77 degrees F], is estimated to be approximately 15 percent using a backfill pressure of 1 atmosphere (atm) [14.7 psi], or 6 percent, using a backfill pressure of 5 atm [73.5 psi]. Further, any residual water in the vapor phase is expected to be spread throughout the cavity and is not expected to be sufficient to provide enough cathodic capacity to initiate and propagate pitting corrosion of the cladding. Confirmation of this expectation is provided in Einziger et al. (2003), which did not observe any evidence of pitting corrosion in cladding after 15 years of dry storage. Therefore, pitting corrosion of the cladding is not considered credible, and aging management is not required during the 60-year timeframe.

3.6.1.8 Galvanic corrosion

Galvanic corrosion can occur due to a mismatch in corrosion potentials between two metals in an aqueous solution. In fuel assemblies, the mismatch can occur when the cladding is in contact with other metallic components, which could result in the formation in a galvanic cell, provided there is an aqueous solution between the two subcomponents. For example, some of the PWR and BWR fuel assemblies contain spacer grids that are made of Inconel alloys, such as Inconel 718 and Inconel 625. The dominant constituents of these Inconel alloys include nickel, chromium, molybdenum, iron, niobium, and tantalum. A galvanic cell could form if residual water condenses in the gap between the rod and a spacer grid, simultaneously contacting both materials. The cladding could also be covered with a crud layer deposit during reactor operations, which could further facilitate formation of the contact.

The standard electrode potential for zirconium and ZrO_2 in aqueous solution at 25 degrees C [77 degrees F] is approximately in the range of −1.5 to −1.6 V_{SHE}, where the subscript “SHE” stands for standard hydrogen electrode (Haynes et al., 2013). The standard electrode potentials for chromium, nickel, molybdenum, and iron are approximately equal to −0.74, −0.20, −0.26, and −0.44 V_{SHE}, respectively, at 25 degrees C [77 degrees F] (Bard and Faulkner, 1980; Haynes et al, 2013). The standard electrode potential data indicate that zirconium would be oxidized to zirconium ions during the galvanic reaction, and oxidizing species, such as oxygen and hydrogen peroxide in aqueous solution, would be reduced at the Inconel alloy. The extent of loss of cladding material would depend on the amount of oxidants present in the condensed water. For example, per the stoichiometry of the oxidation and reduction reactions (Jung et al, 2013), reduction of 1 mole of hydrogen peroxide would result in oxidation of 0.5 mole of zirconium. Similarly, reduction of 1 mole of oxygen would result in oxidation of 1.0 mole of zirconium. Jung et al. reported scoping calculations to determine the extent of zirconium oxidation with 1 mole of a 5 weight percent H_2O_2 aqueous solution saturated with oxygen at 25 degrees C [77 degrees F] and 1 atm [14.7 psi]. Jung et al. concluded that the extent of oxidation would depend on the spread of the condensed water over the large surface area. Therefore, the effect of galvanic corrosion is not expected to be localized.

The amount of residual water inside the cask or canister following drying is expected to be less than 1 mole after vacuum drying, as per guidance in NUREG–1536 (NRC, 2010). Most residual water is expected to decompose over time into hydrogen and oxidizing species, such as oxygen and hydrogen peroxide (Jung et al., 2013). It is possible for some trace amount of water to remain in the vapor phase inside the canister after the first renewal period but is not expected to condense into liquid phase during dry storage due to the low relative humidity of the containment cavity. For example, the relative humidity inside a canister with a cavity volume of 2.1 m^3 [554.8 gal], assuming a residual water content of 0.43 mole (per NUREG–1536) and at 25 degrees C [77 degrees F] is estimated to be approximately 15 percent with a backfill pressure of 1 atm, or 6 percent with backfill pressure of 5 atm [73.5 psi]. Further, any residual water in the vapor phase is expected to be spread throughout the containment cavity and is not expected to be sufficient to form a corrosion cell between the cladding and the spacer grids made of Inconel alloys. Therefore, galvanic corrosion of the zirconium-based cladding alloys is not considered credible, and aging management is not required during the 60-year timeframe.

3.6.1.9 Stress corrosion cracking

SCC occurs as a result of a synergistic combination of a susceptible material, an aggressive environment, and sufficiently high tensile stress. The corrosive environment associated with SCC of fuel rods has been attributed to specific fission products, such as iodine, cesium, and cadmium, generated during reactor irradiation (Wisner and Adamson, 1982; Sidky, 1998). SCC of the cladding can occur at the rod's inner surface where the fuel pellet and cladding mechanically interact and is related to PCMI hoop stresses on the cladding. SCC of zirconium-based cladding has been observed in BWRs during power ramp-up (NRC, 1985; Adamson, 2006). PWR cladding is unlikely to undergo similar SCC because of the more gradual power ramp-up. Fuel pellets in PWR cladding are unlikely to undergo sudden expansion and induce high stresses, as in BWR cladding. No cladding failures from SCC are known to have occurred either during pool storage or under dry storage conditions.

Prescatore and Cowgill (EPRI, 1997) compiled SCC failure data from Yagee et al. (1979, 1980), Mattas et al.(1982), Shimada and Nagai (1983), Kreyns et al. (1976), and Crescimanno (1984) for the following irradiated cladding materials: recrystallized Zircaloy-2, stress-relieved Zircaloy-2, recrystallized Zircaloy-4, and stress-relived Zircaloy-4. For Zircaloy-2, the reported data's temperature and tensile stress ranges were 325 to 350degrees C [617 to 662 degrees F], and 119 to 513 MPa [17.3 to 74.4 ksi], respectively. Similarly for Zircaloy-4, the reported SCC data's temperature and tensile stress ranges were 316 to 350 degrees C [601 to 662 degrees F], and 164 to 414 MPa [23.8 to 60 ksi], respectively. In the listed data, the SCC-induced failure was reported at 157 MPa [22.8 ksi] and 325 degrees C [617 degrees F] for Zircaloy-2, and at 205 MPa [29.7 ksi] and 360 degrees C [680 degrees F] for Zircaloy-4 (Yagee, 1979). Regarding these two failure data points (157 MPa [22.8 ksi] and 325 degrees C [617 degrees F] for Zircaloy-2 and 205-MPa [29.7-ksi] and 360 degrees C [680 degrees F] for Zircaloy-4), Prescatore and Cowgill (EPRI, 1997) argued that failures were misclassified as SCC-induced failures and were more akin to nondetrimental pinhole breaches. Prescatore and Cowgill stated that gross rupture, in the form of axial splitting, was noted in many instances when the stress was greater than about 270 MPa [39.2 ksi], but at lower stresses, pinhole leakage was by far the more common failure mode. If the 157 MPa [22.8 ksi] and 325 degrees C [617 degrees F] data point is excluded from the listed data for Zircaloy-2, as argued by Prescatore and Cowgill, the next incident of the SCC-induced failure is noted at 247 MPa [35.8 ksi] at 325 degrees C [617 degrees F] for Zircaloy-2. Similarly, if the 205 MPa [29.7 ksi] at 360 degrees C [680 degrees F] data point is excluded for Zircaloy-4, as argued by Prescatore and Cowgill, the next incident of the SCC-induced failure is noted at 273 MPa [39.6 ksi] at 360 degrees C [680 degrees F]. This analysis indicates that at least 240 MPa [34.8 ksi] of hoop stresses are needed to induce SCC for both Zircaloy-2 and Zircaloy-4.

Recent work by Raynaud and Einziger (2015) shows that hoop stresses are expected to be below 100 MPa [14.5 ksi], with the most realistic estimate of release of the decay and fission gases from fuel pellets and with the best estimate of fuel swelling during a 300-year dry storage period. However, hoop stresses in ZIRLO™-clad IFBA rods with hollow and solid blanket pellets could be considerably higher. The Raynaud and Einziger study did not account for potential stress concentration effects due to pellet-pellet interfaces and pellet fragment-to-fragment friction forces that could result in more severe PCMI than for a perfectly cylindrical pellet (as assumed in Raynaud and Einziger). Recently, Ahn et al. (2013) estimated stress concentrations from pellet-clad mechanical stresses due to the radiation-induced pellet swelling up to 100 years, independent of hoop stresses due to fission and decay gas release. The work estimated that, for HBU fuel, the average pellet-swelling-induced PCMI stress concentration was on the order of 200 MPa [29 ksi] locally. For low-burnup fuel, pellet expansion stresses will be minimal, because the gap between the cladding and the pellet will accommodate the swelling. Literature indicates that radiation-induced pellet swelling is expected to reach its maximum beyond the first renewal period (Rondinella et al., 2010a,b; 2012). Even with the PCMI-induced hoop stresses, the cladding stresses will remain well below the 240 MPa [34.8 ksi] criterion for inducing SCC. Therefore, SCC of the cladding is not considered credible, and aging management is not required during the 60-year timeframe.

3.6.1.10 Radiation embrittlement

Radiation embrittlement of cladding can result in degradation of the mechanical properties of the cladding, such as ductility and strength (PNNL, 2012; NRC, 2014a). This can lead to the reduction in the maximum load that the cladding can withstand, potentially leaving the cladding vulnerable to failure under external loads.

Radiation embrittlement of the cladding is mostly observed during reactor operation due to cumulative fast neutron fluence on the order of 10^{22} n/cm^2 [6.5 × 10^{22} n/in^2] (Hermann et al., 2001) for recrystallized annealed Zircaloy-2 and cold-worked stress-relieved Zircaloy-4 (Morize et al., 1987). During normal operation in the reactor, the cladding material is bombarded with fast neutrons that cause atomic displacement cascades, resulting in the formation of point defects (PNNL, 2012; NRC, 2014a; NWTRB, 2010). This leads to the reduction in the mechanical properties of the cladding material.

In dry storage, the cumulative neutron fluence is expected be five orders of magnitude less than in reactor service (Jung et al., 2013). In addition, annealing of irradiation hardening could occur during storage, which would help recover some ductility. It has been shown in literature (Masafumi et al., 2007; Torimaru, et al., 1996) that a post-irradiation heat treatment performed at a temperature above the irradiation temperature can lead to the recovery of the radiation-induced hardening and increased ductility of the cladding. Ito et al. (2004) further showed that hardness also recovers at temperatures lower than an irradiation temperature of 360 degrees C [680 degrees F]. More specifically, Ito et al. (2004) showed that hardness continued to recover, albeit quite slowly, at temperatures as low as 330 degrees C [626 degrees F] for 8,000 hours (0.9 year), and nearly 50 percent recovery was observed compared to the annealing over the same time at 360 degrees C [680 degrees F]. Thus, over many years of extended storage, it is possible that thermal annealing could increase cladding ductility, thereby reducing the effects of radiation embrittlement.

Because radiation embrittlement is associated with a cumulative fluence of on the order of 10^{22} n/cm^2 [6.5 × 10^{22} n/in^2], which is not expected during storage, radiation embrittlement of cladding is not considered credible, and therefore, aging management is not required during the 60-year timeframe.

3.6.1.11 Fatigue

Fatigue occurs when a material is subjected to repeated loading and unloading stresses. If the loads are above a certain threshold, microscopic cracks will begin to form at stress concentrators at the surface, persistent slip bands, and grain interfaces. As a crack reaches a critical size, it will propagate until fracture. Because dry storage is a passive application, purely mechanical cyclic loading is not expected. However, the cladding will experience thermal cycles due to daily and seasonal fluctuations in ambient temperature, as well as extreme weather events within a larger seasonal pattern. These thermal cycles will induce cyclic stresses on the cladding due to either (i) changes in fission and decay gas pressure, as governed by gas laws, which would result in fluctuations in cladding hoop stresses, and (ii) partial restraint on cladding thermal expansion and contraction due to top and bottom nozzles, hold-down springs, and spacer grids. These thermally induced stresses and corresponding strains can produce fatigue damage in the same manner as purely mechanical cyclic loading.

Devoe and Robb (2015) conducted steady-state analyses to show that the change in peak cladding temperature is directly proportional to the change in external air temperature of the canister. Although the large thermal mass of the DSS is likely to reduce the amplitude and frequency of the thermal cycles on fuel and cladding temperature, Devoe and Robb assumed a correlation coefficient of unity between the peak cladding and external air temperature. Thus, a 1 degree C [1.8 degree F] change in air temperature would result in approximately 1 degree C [1.8 degree F] change in cladding temperature. When evaluating daily temperature fluctuations, the analysis assumed a conservative 25 degrees C maximum daily change [equivalent to 45 degrees F change], which is the mean daily temperature change in the United States. The model further assumes a total of 21,900 thermal cycles, corresponding to steady-state temperature cycle every day for 60 years. The staff assumed these conditions to determine if the resulting changes in cladding hoop stresses could lead to fatigue-induced failure of the cladding.

Raynaud and Einziger (2015) estimated the cladding hoop stresses while accounting for release of fission gases and decay gases during storage, including pellet swelling stresses due to radiation damage during storage. Raynaud and Einziger estimates included the effect of fuel temperature on cladding hoop stresses. As per the Raynaud and Einziger estimates, a 25 degree C variation [45 degree F variation] in cladding temperature will cause up to 10 and 30 MPa [1.45 and 4.35 ksi] fluctuations in hoop stress of the BWR and PWR claddings, respectively. Lin and Haicheng (1998) conducted experimental studies to determine fatigue properties of zirconium and Zircaloy-4. Lin and Haicheng (1998) provided a fatigue lifetime curve for zirconium and Zircaloy-4 under reversal bending as a function of the cyclic stress. As per the fatigue lifetime curve in Lin and Haicheng, a cyclic stress amplitude of more than 260 MPa [37.7 ksi] is needed for fatigue-induced failure in Zircaloy-4 in 10^7 cycles. The curve also bounds the data for zirconium, and hence, is also assumed to be applicable for other zirconium-based cladding materials, such as Zircaloy-2, ZIRLO™, and M5®. Therefore, using the fatigue lifetime curve in Lin and Haicheng, these fluctuations in hoop stresses (per the assumed conditions in Devoe and Robb, 2015) are not sufficient for fatigue-induced failure in the cladding.

The staff also evaluated the effects of extreme seasonal temperature variations, as these are expected to be significantly higher than daily variations and could result in higher cyclic stress amplitudes. Using the off-normal DSS operating conditions of −40 degrees C [−40 degrees F] (winter) and 103 degrees C [217 degrees F] (summer) yields a maximum seasonal temperature variation of 143 degrees C [variation of 257 degrees F]. Similar to the previous analysis, per the Raynaud and Einziger (2015) estimates, a 143 degree C variation [257.4 degree F variation] in cladding temperature will cause up to 10 and 55 MPa [1.45 and 7.8 ksi] fluctuations in hoop stress of the BWR and PWR claddings, respectively. Using the fatigue lifetime curve in Lin and Haicheng (1998), these fluctuations in hoop stresses (per the assumed conditions in Devoe and Robb, 2015) are also not sufficient for fatigue-induced failure in the cladding.

As discussed in Section 3.2.1.7, the cyclic stress, σ, induced by the thermal variations also depends on the material's coefficient of thermal expansion (α_0) and Young's modulus of elasticity (E), the actual change in temperature (ΔT), and the degree of constraint on the component. Since the degree of constraint for the cladding is not readily available for cladding, a conservative approach is employed to estimate the cyclic stresses and associated potential impact of thermal fatigue. The coefficient of thermal expansion is estimated to be approximately 4.16×10^{-6}/K, based on the data in Luscher and Geelhood (2010). The Young's modulus of elasticity of various zirconium-based cladding materials ranges between 32 and 100 GPa [4,641 and 14,504 ksi] (Luscher and Geelhood, 2010); a value of 100 GPa [14,504 ksi] is conservatively used. The assumed values of α_0 and E result in a thermally induced cyclic stress of 10.4 MPa [1.5 ksi] and 59.5 MPa [8.6 ksi] for ΔT equal to 25 and 143 degrees C [45 and 257 degrees F] , respectively. As per the fatigue lifetime curve in Lin and Haicheng (1998), these fluctuations in hoop stresses are also not sufficient for fatigue-induced failure in the cladding.

The staff further considered the cumulative cyclic stresses for all cases described above, which results in stresses ranging from 20 to 70 MPa [2.9 and 10.2 ksi] for BWR and from 65 to 115 MPa [9.4 and 16.7 ksi] for PWR claddings. Even the combined conservative values are well below the threshold of 260 MPa [37.7 ksi] needed for fatigue-induced failure in the cladding, per Lin and Haicheng (1998). Therefore, the staff concludes that fatigue-induced failure of the cladding is not credible during the 60-year timeframe, and aging management is not required.

3.6.2 Assembly hardware materials

The assembly hardware considered here includes guide tubes, spacer grids, and lower and upper end fittings. The guide tubes are fabricated using zirconium-based alloys. The other components are fabricated using one of the following materials: zirconium-based alloys, Inconel 718, Inconel 625, Inconel X-750, and stainless steel 304L. These subcomponents are not expected to experience sustained external loads during passive dry storage except for their own weight.

3.6.2.1 Creep

Creep is defined as the time-dependent deformation that takes place at an elevated temperature and constant stress. Because the deformation processes that produce creep are thermally activated, the rate of this time-dependent deformation (i.e., the creep rate) is a strong function of the temperature. The creep rate also depends on the applied stress but does not generally vary with the environment. As a general rule of thumb, at temperatures below $0.4T_m$, where Tm is the melting point of the metal in Kelvin, thermal activation is insufficient to produce significant creep (Cadek, 1988). The melting temperature of various zirconium alloys is above 1,800 degrees C [3,272 degrees F]. Similarly, the melting temperature of various Inconel alloys is above 1,260 degrees C [2,300 degrees F]. In addition, the melting temperature of 304L stainless steels is close to 1,400 degrees C [2,552 degrees F].

Regarding the zirconium alloys, the $0.4T_m$ criterion yields a creep threshold of 556 degrees C [1,033 degrees F]. The maximum expected temperature of fuel cladding has been estimated to be 400 degrees C [752 degrees F] at the beginning of storage (Jung et. al., 2013). This cladding temperature is expected to decrease to around 266 degrees C [510 degrees F] after 20 years and to approximately 127 degrees C [261 degrees F] after 60 years. This indicates that creep of the zirconium alloys is unlikely during the renewal period.

Regarding Inconel alloys, the $0.4T_m$ criterion yields a creep threshold of 340 degrees C [644 degrees F]. As stated previously, the peak temperature inside the storage canister is expected to be below 266 degrees C [510 degrees F] after 20 years of storage. This indicates that creep of various Inconel alloys is unlikely during the renewal period.

Regarding 304L stainless steel, the $0.4T_m$ criterion yields a creep threshold of 396 degrees C [755 degrees F]. As stated previously, the peak temperature inside the storage canister is expected to be below 300 degrees C [572 degrees F] after 20 years of storage. Further, the $0.4T_m$ rule of thumb underestimates the minimum creep temperature for steels, because temperatures above 500 degrees C [932 degrees F] are required for significant creep in steels (Samuels, 1988). This indicates that creep of 304L stainless steel is unlikely during the renewal period.

Therefore, creep of the assembly hardware is not considered credible, and aging management is not required during the 60-year timeframe.

3.6.2.2 Hydriding

Assembly hardware such as guide tubes and spacer grid materials made from zirconium alloys could potentially be subjected to hydriding effects that could reduce the material's ductility and fracture toughness, particularly at lower temperatures (less than 200 degrees C [392 degrees F]), once the fuel has cooled (PNNL, 2012).

Hydriding may occur in zirconium alloys that experience hydrogen pickup in reactor service (NRC, 2014a). As the temperature of the assembly hardware decreases, zirconium hydrides precipitate due to the decreasing hydrogen solubility in the zirconium matrix. The hydride precipitation will occur when the hardware cools in the spent fuel pools after reactor discharge. Some of the hydride will dissolve during the drying process and will reprecipitate due to subsequent cooling during storage. Unlike fuel rods with cladding, there is no hoop stress for the zirconium-based assembly hardware to cause hydride reorientation. Any load on the assembly hardware is predominantly expected due to its own weight, which is not sufficient to be equivalent to hoop stresses to cause hydride reorientation. In addition, any additional hydriding of the assembly hardware during extended storage is expected to be negligible (Jung et al., 2013).

In summary, the impact of hydriding effects on assembly hardware, especially guide tubes, is far less severe than for cladding with fuel (EPRI, 2011; PNNL, 2012; Hanson et al., 2012). Because there is limited load during storage on assembly hardware, it is unlikely that hydriding will affect the ability of the assembly hardware to ensure that the spent fuel remains in the as-analyzed configuration. Confirmation of this expectation is provided by Einziger et al. (2003), which did not observe any hydriding effects on assembly hardware after 15 years of dry storage. Therefore, hydriding of assembly hardware components is not considered to be significant, and aging management is not required during the 60-year timeframe.

3.6.2.3 General corrosion

Various assembly hardware components made of stainless steel or Inconel may be subjected to general corrosion in the presence of humid air or an aqueous solution. General corrosion of assembly hardware made of zirconium alloys is not considered here; it is excluded per the technical basis discussed in Section 3.6.1.6. The amount of residual water in the canister during the extended storage is expected to be less than 1 mole per the guidance in NUREG–1536 (NRC, 2010). Most residual water is expected to decompose into hydrogen and oxidizing species, such as oxygen and hydrogen peroxide, with time (Jung et al., 2013). However, it is possible for trace amounts of water to remain in the vapor phase in the canister's internal environment for the extended period.

The general corrosion rate of the nickel-based Inconel alloys due to humid air is expected to be on the order of 25 nm/yr [10^{-3} mils/yr] (Van Rooyen and Copson, 1968). The general corrosion rate of 304 stainless steel in the presence of humid air has been reported to be negligible (INCO, 1970), and the low-carbon grade 304L is expected to behave similarly. Further, as corrosion proceeds, the residual water would deplete with time. Considering the low general corrosion rate of the Inconel alloy, the negligible corrosion rate of 304 stainless steel under humid air conditions, and the radiolysis of the residual water, it is concluded that the effect of general corrosion in the presence of trace amounts of water is insignificant on assembly hardware components during the renewal period. As such, general corrosion of assembly hardware is considered to be insignificant, and therefore, aging management is not required during the 60-year timeframe.

3.6.2.4 Stress corrosion cracking

Various stainless steel and Inconel assembly hardware components could be susceptible to SCC in the presence of an aggressive environment and sufficient residual tensile stresses. SCC of the structural components may lead to cracking, which can compromise the structural integrity of the component. SCC of assembly hardware made of zirconium alloys is not considered here; it is excluded per the technical basis discussed in Section 3.6.1.9.

Residual tensile stresses are expected to be present in the assembly hardware, primarily in welded areas. Regarding the chemical environment, various types of stainless steels are prone to SCC, even in high-purity demineralized water at the temperatures of the BWRs, typically 290 degrees C [554 degrees F] (Kain, 2011). This observation is attributed to the presence of dissolved oxygen and other oxidizing species in the primary coolant water (Kain, 2011) of a BWR. Various types of nickel-based alloys, including Inconel, are susceptible to SCC in the presence of hot water, hot caustic solution, hot wet hydrofluoric acid solution, or aqueous solution containing a sufficient amount of chloride at high temperatures (Rebak, 2011).

In the canister environment, the water could exist in the liquid state only when the temperature is near or below 100 degrees C [212 degrees F]. The residual water content inside the canister is expected to be less than 1 mole during dry storage, as per guidance in NUREG–1536 (NRC, 2010). During storage, most residual water would decompose into hydrogen and oxidizing species, such as oxygen and hydrogen peroxide, due to radiolysis (Jung et al., 2013). However, it is possible for a trace amount of residual water to persist in the vapor phase of the containment cavity. The trace amount of water is unlikely to condense into the liquid phase during dry storage because the relative humidity of the DSS internal environment cannot reach 100 percent when the residual amount of water is less than 1 mole. For example, the relative humidity inside a containment cavity volume of 2.1 m^3 [554.8 gal] at 25 degrees C [77 degrees F], assuming a residual water amount of 0.43 mole [expected after vacuum drying as per NUREG–1536], is estimated to be approximately 15 percent, using a backfill pressure of 1 atm [14.7 psi], or 6 percent using a backfill pressure of 5 atm [73.5 psi] (Green and Perry, 2007). Further, SCC of stainless steel and Inconel has not been reported in a nonchloride humid air environment.

Because of the lack of halides and the small amount of water in helium and embedded environments, SCC of stainless steel is not considered to be credible. Therefore, aging management of SCC of stainless steel subcomponents exposed to helium is not required during the 60-year timeframe.

3.6.2.5 Radiation embrittlement

Radiation embrittlement of assembly hardware such as guide tubes and spacer grid materials made from zirconium alloys is excluded using the basis provided in Section 3.6.1.10. Similarly, radiation embrittlement of assembly hardware made of stainless steel or Inconel is not considered credible per the technical bases provided in Sections 3.2.1.9, 0, and 0. Therefore, aging management of radiation embrittlement of assembly hardware subcomponents exposed to helium and embedded environments is not required during the 60-year timeframe.

3.6.2.6 Fatigue

Fatigue of assembly hardware such as guide tubes and spacer grid materials made from zirconium alloys is excluded using the basis provided in Section 3.6.1.11. Similarly, fatigue of assembly hardware made of stainless steel or Inconel is not considered credible per the technical bases provided in Sections 3.2.1.7, 3.2.2.7, and 3.2.4.5. Therefore, aging management of fatigue of assembly hardware subcomponents exposed to helium is not required during the 60-year timeframe.

3.6.3 References

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4 ANALYSIS OF DRY STORAGE SYSTEMS AND SPENT FUEL ASSEMBLIES

4.1 Introduction

This chapter provides (1) a brief description of selected storage system designs and (2) aging management tables for each design that identify the aging mechanisms and effects that must be managed to ensure that the functions of structures, systems, and components (SSCs) are maintained in the period of extended operation. The analyses in Chapter 3 provide the technical bases for those determinations. The aging management tables also identify the use of either a time-limited aging analysis (TLAA), aging management program (AMP), or other analysis to address the aging effects that require management.

The following system descriptions are for general information only. In the review of a renewal application, the technical reviewer should refer to the application, safety analysis report, and drawings to identify the SSCs within the scope of renewal and their functions, materials of construction, and operating environment. Table 4-1 describes the storage system designs that are discussed below and evaluated in the aging management tables.

Table 4-1 Evaluated storage system designs

MAPS Section No.	Name	NRC Docket No.	Amendments Evaluated
4.2	Standardized NUHOMS®*	72-1004	1–11 and 13
	Standardized Advanced NUHOMS®	72-1029	1 and 3
4.3	HI-STORM 100	72-1014	1–10
	HI-STAR 100	72-1008	1–2
4.4	TN-32	72-1021	1
	TN-68	72-1027	1
4.5	NAC-UMS	72-1015	1–5
	NAC-MPC	72-1025	1–6
	MAGNASTOR	72-1031	1–6
4.6	FuelSolutions	72-1026	1–4
4.7	Concrete Pad (generic)	—	—
4.8	Spent Fuel Assemblies (generic)	—	—

*The staff's review of the Calvert Cliffs specific license renewal application (NRC, 2014) informed the evaluation of the NUHOMS system, and thus the aging management tables for this system may include some unique elements of this site.

4.2 NUHOMS® systems: Standardized and Standardized Advanced

4.2.1 System description

The NUHOMS family of modular storage systems provide for the horizontal storage of spent nuclear fuel (SNF) in a dry shielded canister (DSC) that is placed in a concrete horizontal storage module (HSM). Each NUHOMS system model type is designated by NUHOMS-XXY. The two digits (XX) refer to the number of fuel assemblies stored in the DSC, and the character (Y) designates the type of fuel being stored—P for pressurized-water reactor (PWR) or B for boiling-water reactor (BWR). For some systems, a fourth character (T) is added to designate that the DSC is also intended for transportation in packages approved under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 71,"Packaging and Transportation of Radioactive Material." Also, two additional characters, HB, are added for systems that are used to store high-burnup fuels (e.g., NUHOMS-24PHB).

The Standardized NUHOMS design is presently licensed for use in the United States under NRC Docket 72-1004, in combination with the 24P, 24PT2, 24PHB, 24PTH, 32PT, 32PTH1, 37PTH, 52B, 61BT, 61BTH, and 69BTH DSCs, while the Standardized Advanced NUHOMS design is licensed for use under NRC Docket 72-1029, with the 24PT1, 24PT4, and 32PTH2 DSCs. The principal components of the NUHOMS system include (i) a stainless steel DSC with an internal basket to hold SNF assemblies, (ii) a structural steel assemblage that supports the DSC, and (iii) an HSM that is constructed of reinforced concrete (see Figure 4-1). Additional components include an onsite transfer cask (TC) and other fuel transfer and auxiliary equipment used to support DSC loading and transfer operations.

The Standardized Advanced system differs from the Standardized system in that it includes modifications to accommodate sites with high seismic levels, limited space, and needs for enhanced radiation shielding performance. To accomplish this, a modified version of the HSM was created, designated as the Advanced Horizontal Storage Modulue (AHSM). A brief summary of the components of the NUHOMS storage systems are provided below.

4.2.2 Dry shielded canister

The NUHOMS DSC is a welded stainless steel canister that uses redundant multipass closure welds. After fuel loading, draining and drying, the canister is backfilled with helium to provide an inert environment. Figure 4-2 and Figure 4-3 show the components of two DSC configurations, which comprise the shell assembly and the internal basket assembly.

Shell assembly

The DSC shell assembly consists of a stainless steel cylindrical shell that is joined to top and bottom end assemblies with double, redundant seal welds to form the confinement boundary. The bottom end assembly welds are made during fabrication of the DSC, while the top end assembly welds are made after fuel loading. The shell assembly also includes two shielding plugs at both ends for biological shielding. Siphon and vent ports penetrate the top shield plug and are sealed after DSC drying operations are complete. Figure 4-4 shows the pressure and confinement boundaries for the NUHOMS-32PT DSC.

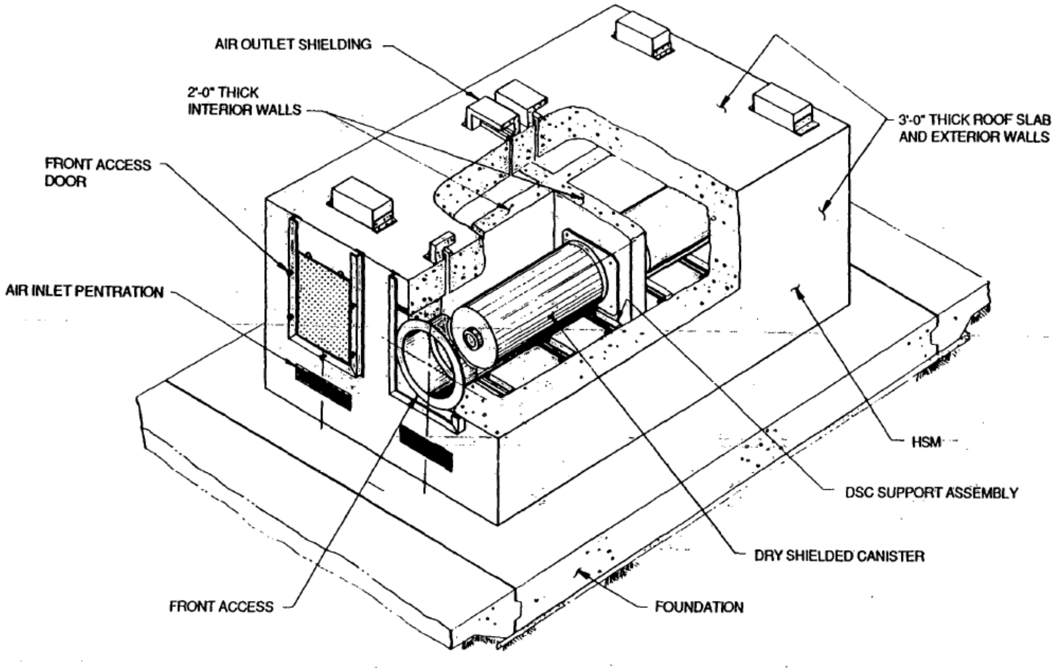


Figure 4-1 NUHOMS dry storage system (Pacific Nuclear Fuel Services, Inc., 1991)

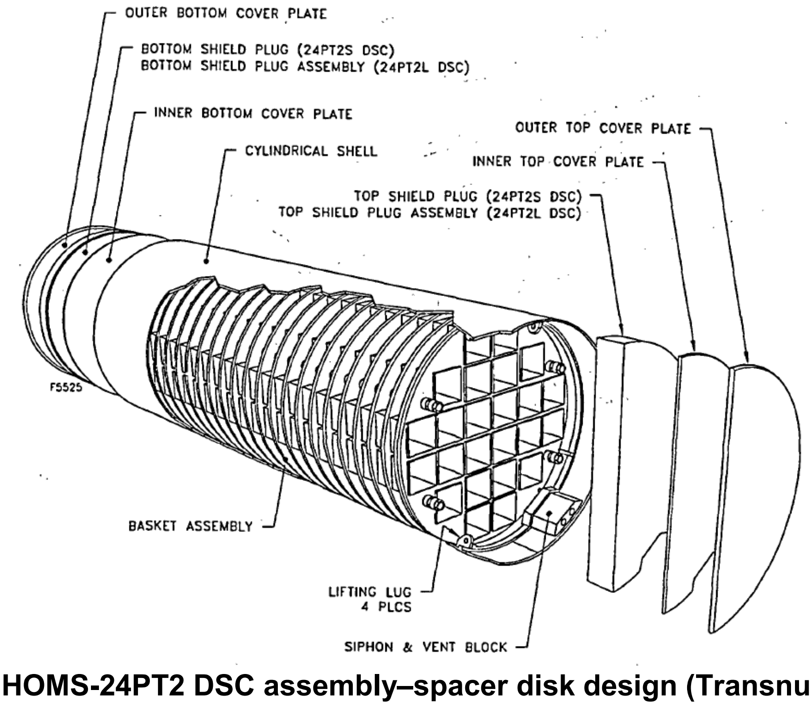


Figure 4-2 NUHOMS-24PT2 DSC assembly–spacer disk design (Transnuclear, 2004)

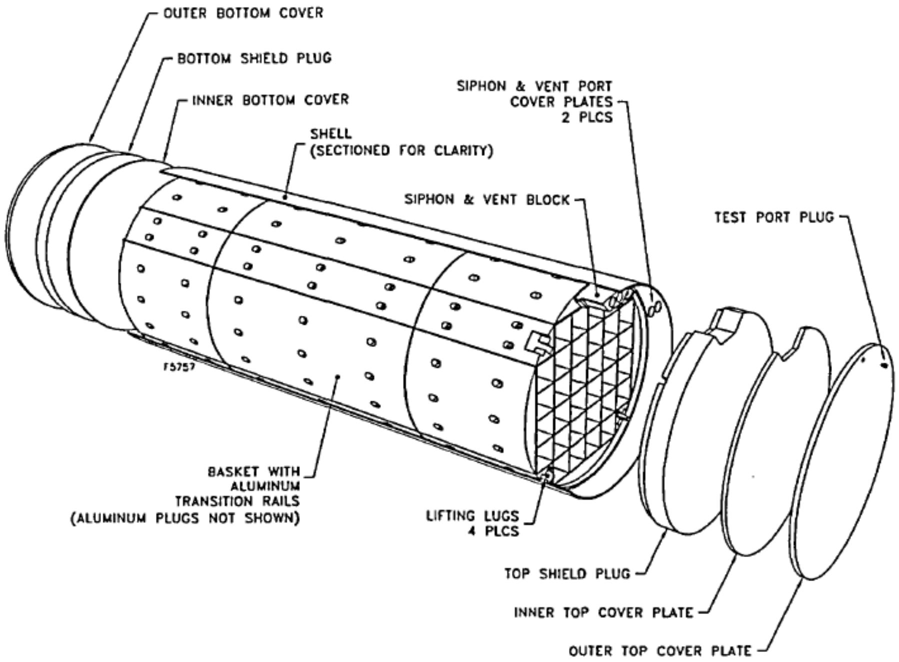


Figure 4-3 NUHOMS-32PT DSC assembly–tube or plate design (Transnuclear, 2004)

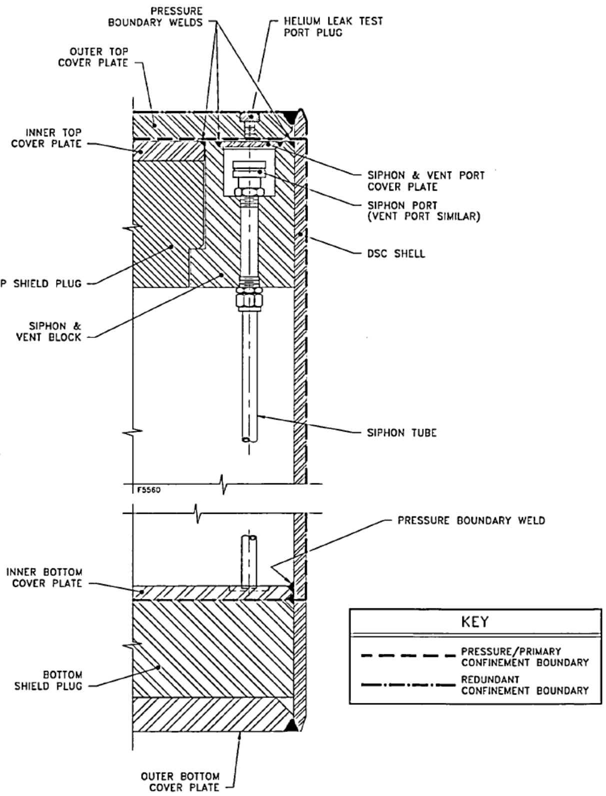


Figure 4-4 Pressure and confinement boundaries for NUHOMS-32PT DSC (Transnuclear, 2004)

Internal Basket Assembly

The internal basket assembly contains a storage position for each fuel assembly. The basket assembly may consist of an assemblage of spacer disc plates supported on vertical rods that extend the length of the DSC cavity (spacer disc design) or individual tubes or plates welded to form a grid-like structure (tube or plate design).

The 24P, 24PT1, 24PT2, 24PT4, 24PHB, and 52B DSCs use the spacer disc basket design, as shown in Figure 4-2. Subcriticality is maintained through the geometric separation of the fuel assemblies by the DSC basket assembly and the neutron absorbing capability of the DSC materials of construction. The 52B DSC contains fixed neutron poison material for additional criticality control.

The 61BT, 32PT, 24PTH, 61BTH, 32PTH1, 32PTH2, 69BTH, and 37PTH DSCs use the tube or plate grid basket design, as shown in Figure 4-3. Fixed neutron poison material provides the necessary criticality control. Aluminum sheets or plates are used to provide the heat conduction paths from the fuel assemblies to the canister shell. Transition rails, consisting of welded stainless steel plates or aluminum parts, form the transition between the box-like fuel compartment structure and the cylindrical DSC shell.

Table 4-2 and Table 4-3 evaluate potential aging mechanisms and effects requiring management for specific components of the Standardized and Standardized Advanced NUHOMS DSC shell and basket designs. The tables also identify AMPs that provide an acceptable approach to managing the aging effects.

4.2.3 Horizontal storage module

Both the HSM and AHSM storage modulus are low-profile structures constructed from reinforced concrete and structural steel that provides a means for passive removal of spent fuel decay heat, structural support and environmental protection of the DSC, and radiation shielding. The AHSM design is similar to the HSM; however, the AHSM contains improved shielding and resistance to high seismic events. The AHSM consists a base storage unit and a top shield block that is tied to the base unit by steel rods in the vertical direction and interlocking concrete keys in the horizontal direction.

Heat removal is achieved by a combination of radiation, conduction, and convection. As shown in Figure 4-5 and Figure 4-6, ambient air enters the HSMs through ventilation inlet openings located in the lower region of the front or side walls and circulates around the DSC. Air exits through outlet openings in the top regions of the HSM walls. Thermal monitoring or visual inspections are used to provide indication of HSM performance or a blocked vent condition. Environmental protection and radiation shielding are provided by the thick side walls and roof of the HSM, supplemented by thick wall units attached at the ends of the array and at the rear walls of the HSM if the array is of single row configuration. Each HSM has an access opening or docking flange in the front wall to accommodate transfer of DSCs from and into the shielded TC. The access opening is covered by a thick shielded access door.

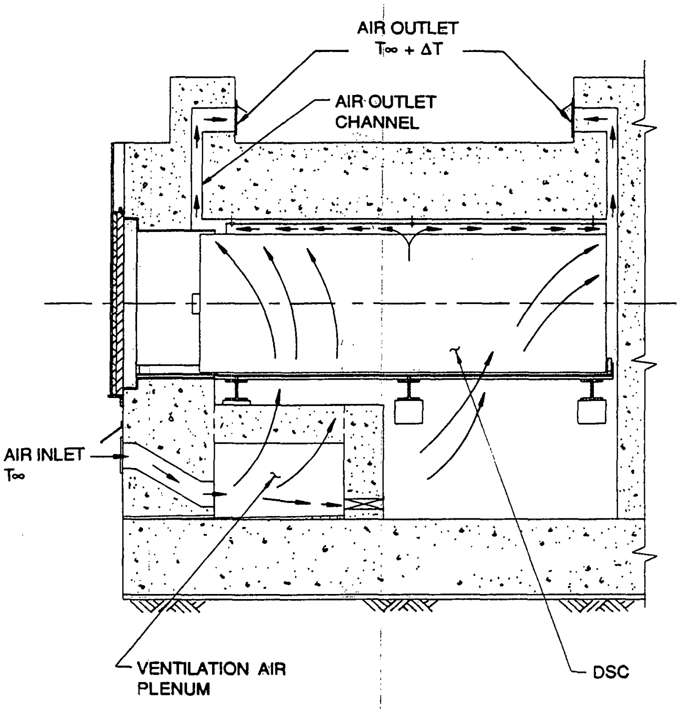


Figure 4-5 Air flow diagram for a typical standardized HSM design (Pacific Nuclear Fuel Services, Inc., 1991)

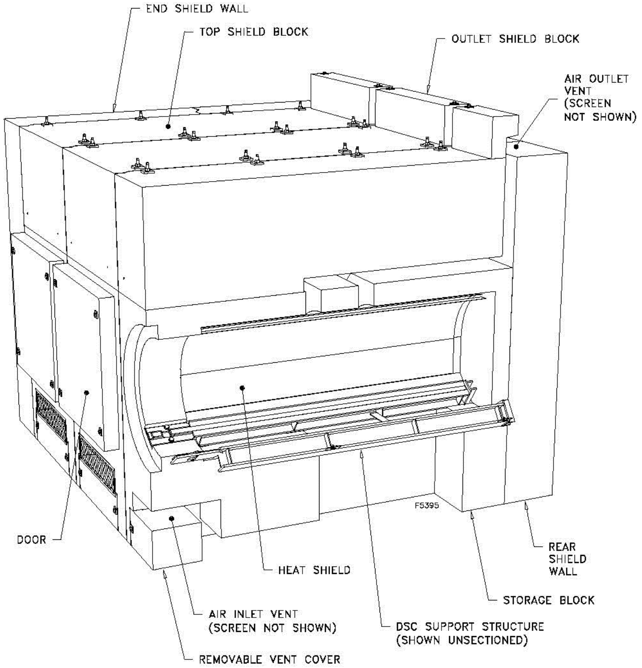


Figure 4-6 Advanced NUHOMS horizontal storage module (AHSM) (Transnuclear, 2003)

Structural support of the loaded DSC is provided by a structural steel frame structure (HSM model 80 and model 102) anchored to the floor slab and walls of the HSM, or a structural steel rail assembly (HSM models HSM-H, -152, -202, HSM-HS, AHSM, and AHSM-HS). Figure 4-7 shows drawings of the side elevation and end view of the DSC rail assembly. Stainless steel cover plates coated with a dry film lubricant are attached to the rails to provide a sliding surface for DSC insertion and retrieval. In some designs, Nitronic 60 plates are welded to the cover plates because of this material's good high-temperature properties and resistance to oxidation, wear, and galling. Seismic restraints using steel plates or tubes are welded to the rear and front of the rails for retaining the DSC in place during seismic events.

Table 4-4 and Table 4-5 provide a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the Standardized NUHOMS HSM and Standardized Advanced NUHOMS AHSM. The tables also identify the AMPs that provide an acceptable approach to managing the effects of aging.

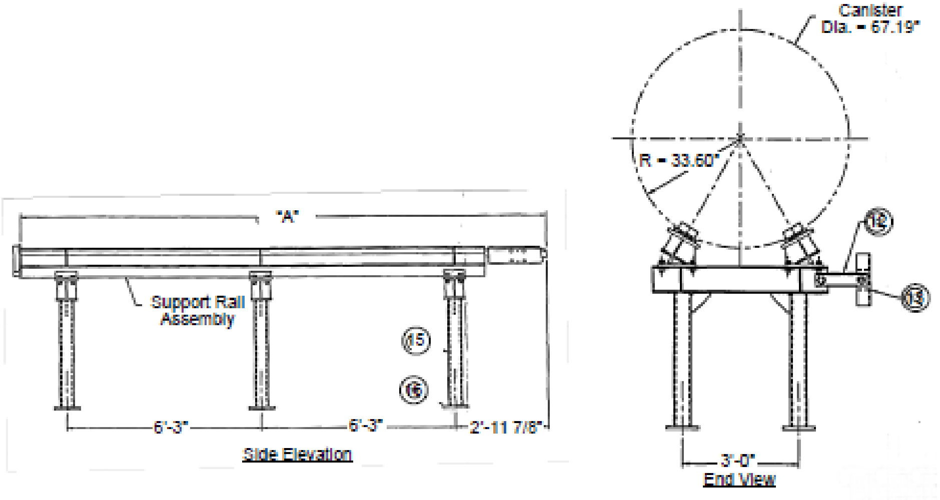


Figure 4-7 Side elevation and end view of the DSC support structure (Transnuclear, 2004)

4.2.4 Transfer cask

The NUHOMS TC is a cylindrical vessel with a bolted top cover plate and a welded bottom end assembly (Transnuclear, 2014). There are five alternate configurations of the cask.

- The basic configuration, where the TC is provided with a solid neutron shield, is denoted as the standardized onsite cask.
- A second configuration includes the OS197 and OS197H (H: modified for increased strength), in which water is used to provide neutron shielding.
- The third configuration, designated as OS197FC, OS197HFC OS197FC-B, or OS197HFC-B TC, is equipped with a modified top lid to allow air circulation through the annulus between the DSC and the TC.
- The fourth configuration, designated as OS197L TC and shown in Figure 4-8, is a reduced weight version of the OS197 TC.

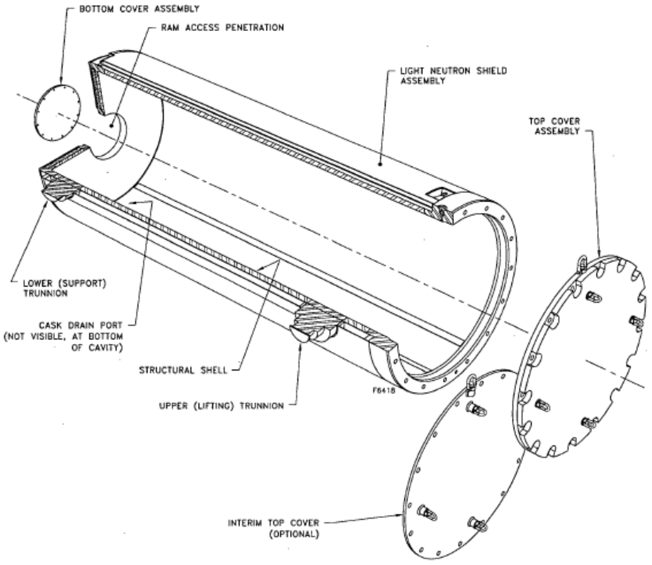


Figure 4-8 OS197L transfer cask (Transnuclear, 2008)

- The fifth configuration is designated as OS200 or OS200FC TC and has a larger diameter to accommodate the larger diameter DSCs with 32PTH1, 37PTH, or 69BTH SNF assemblies.

For all the configurations except the OS197L TC, the TCs are constructed from two concentric cylindrical shells: a stainless steel inner shell and a structural shell made of stainless steel or carbon steel. The annulus formed by these two shells is filled with cast lead to provide gamma shielding. The TC also includes an outer jacket made of stainless steel or carbon steel, which is filled with BISCO NS-3 material or water for neutron shielding. The inner and structural shells are welded to heavy forged ring assemblies at the top and bottom ends. The bottom end plate has a removable stainless steel ram access penetration ring. A stainless steel bottom cover plate is provided to seal the hydraulic ram access penetration of the cask during fuel loading. Rails fabricated from a nongalling, wear-resistant stainless steel coated with a high contact pressure dry film lubricant are provided to facilitate DSC transfer.

The OS197L TC is constructed from a single, thicker stainless steel structural shell. To compensate for the lack of lead shielding, the OS197L TC relies on the use of supplemental shielding in conjunction with remote operations during handling in the fuel or reactor building, transfer to the ISFSI, and insertion into the HSM operations. The cask support skid supplemental shielding consists of a thick carbon steel upper shielding bell and a lower shielding sleeve that enclose the TC in the decontamination area, and thick carbon steel plates and covers that enclose the TC while on the transfer trailer.

The NUHOMS TCs have four trunnions made of stainless steel or nickel alloy that are welded to the structural shell. Two upper lifting trunnions are located near the top of the cask for lifting the cask in the SNF pool building. The lower trunnions, located near the base of the cask, serve as the axis of rotation and as supports during transport to the HSM.

Table 4-6 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the NUHOMS transfer casks. The table also identifies the AMPs that provide an acceptable approach to managing the aging effects.

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Guide sleeves (DSC basket)	CR, SR, TH*	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Oversleeves (DSC basket)	CR, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Aluminum plate or sheet, basket plate, compartment plate (DSC basket)	CR, SH, TH	Aluminum	Helium	Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				General corrosion	Loss of material	No	3.2.3.1
				Radiation embrittlement	Cracking	No	3.2.3.8
Spacer disks (DSC basket)	CR, SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in Dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Spacer disks (DSC basket)	CR, SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Support rods (DSC basket)	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Stainless steel (welded 17-4 PH)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.2.2.8
		Stainless steel (17-4 PH)	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Spacer sleeves (DSC basket)	CR, SR	Stainless steel (welded 17-4 PH)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Basket rails (DSC basket)	CR, SH, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Basket rail inserts and shims (DSC basket)	SR, TH	Aluminum	Helium	Thermal aging	Loss of strength	TLAA/AMP or a supporting analysis is required	3.2.3.7
				Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5
				General corrosion	Loss of material	No	3.2.3.1
				Radiation embrittlement	Cracking	No	3.2.3.8
Basket assembly plates (DSC basket)	CR, SH, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Grid assembly (DSC basket)	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Holddown ring assembly and plates (DSC basket)	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel compartment tubes, wraps, inserts (DSC basket)	CR, SH, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Transition rails (DSC basket)	CR, SH, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Aluminum	Helium	Thermal aging	Loss of strength	TLAA/AMP or a supporting analysis is required	3.2.3.7
				Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5
				General corrosion	Loss of material	No	3.2.3.1
				Radiation embrittlement	Cracking	No	3.2.3.8

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron absorbing plates, poison plates (DSC basket)	CR, TH	Borated stainless steel	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.4.1.3
				Creep	Change in dimensions	No	3.4.1.2
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.1.4
Neutron absorbing plates or sheets, poison plates, chevron neutron absorbers (DSC basket)	CR, SH, TH	Boralyn®, Metamic™	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6
				General corrosion	Loss of material	No	3.4.2.1
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7
		Boral®	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6
				Wet corrosion and blistering	Change in dimensions	No	3.4.2.3
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron absorbing plates or sheets, poison plates, chevron neutron absorbers (DSC basket)	CR, SH, TH	Borated aluminum	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6
				General corrosion	Loss of material	No	3.4.2.1
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7
Support bars (DSC basket)	SR	Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Fastener components	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fastener components	SR	Steel	Helium	Radiation embrittlement	Cracking	No	3.2.1.9
Tool socket and closure plate	SR	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Components for damaged fuel	CO, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Cover plates (inner)	CO, SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in Dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Shield plug (top)	CO, SH, SR, TH	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield plug (top)	CO, SH, SR, TH	Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Shield plug (bottom)	CO, SH, SR, TH	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Lead shielding	SH	Lead	Embedded (steel, stainless steel)	None identified	None identified	No	3.2.6

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Siphon and vent block	CO, SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Siphon and vent port cover plate	CO, SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Test port plug	CO	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Key, shear key	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Pin, anti-rotation pin	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
DSC support ring	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in Dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Lifting lugs	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
DSC shell	CO, SH, SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
DSC shell	CO, SH, SR, TH	Stainless steel	Sheltered	Galvanic corrosion	Loss of material	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Cover plates (outer)	CO, SH, SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-2 Standardized NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Grapple ring and grapple support	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Guide sleeves (DSC basket)	CR, SR, TH*	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Oversleeves, stop plates (DSC basket)	CR, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Spacer disks (DSC basket)	CR, SR	Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Support rods (DSC basket)	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Support rods (DSC basket)	CR, SR	Stainless steel (welded 17-4 PH)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.2.2.8
		Stainless steel (17-4 PH)	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Spacer sleeves (DSC basket)	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Stainless steel (welded 17-4 PH)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.2.2.8
		Stainless steel (17-4 PH)	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Shims (DSC basket)	SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Aluminum	Helium	Thermal aging	Loss of strength	TLAA/AMP or a supporting analysis is required	3.2.3.7

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shims (DSC basket)	SR, TH	Aluminum	Helium	Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5
				General corrosion	Loss of material	No	3.2.3.1
				Radiation embrittlement	Cracking	No	3.2.3.8
Basket assembly plates (DSC basket)	CR, SH, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Aluminum	Helium	Thermal aging	Loss of strength	TLAA/AMP or a supporting analysis is required	3.2.3.7
				Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5
				General corrosion	Loss of material	No	3.2.3.1
				Radiation embrittlement	Cracking	No	3.2.3.8
Fuel compartment (DSC basket)	CR, SH, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Transition rails (DSC basket)	CR, SH, SR, TH	Aluminum	Helium	Thermal aging	Loss of strength	TLAA/AMP or a supporting analysis is required	3.2.3.7
				Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5
				General corrosion	Loss of material	No	3.2.3.1
				Radiation embrittlement	Cracking	No	3.2.3.8
Neutron absorbing poison plate (DSC basket)	CR, SH, TH	Boron carbide/ aluminum metal-matrix	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6
				General corrosion	Loss of material	No	3.4.2.1
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7
Neutron absorbing sheets (DSC basket)	CR, SH, TH	Boral®	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6
				Wet corrosion and blistering	Change in dimensions	No	3.4.2.3

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron absorbing sheets (DSC basket)	CR, SH, TH	Boral®	Helium	Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7
Fastener components	SR	Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Components for damaged fuel	CO, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Cover plates (inner)	CO, SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Cover plates (inner)	CO, SH, SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Shield plug (top)	CO, SH, SR, TH	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Shield plug casing (bottom)	CO, SH, SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield plug casing (bottom)	CO, SH, SR, TH	Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.2.9
Shield plug (bottom)	CO, SH, SR, TH	Steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				General corrosion	Loss of material	No	3.2.1.1
				Radiation embrittlement	Cracking	No	3.2.1.9
Lead shielding	SH	Lead	Embedded (stainless steel)	None identified	None identified	No	3.2.6
Siphon and vent block	CO, SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Siphon and vent block	CO, SH, SR	Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Siphon and vent port cover plate	CO, SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Test port plug	CO	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Pin	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
DSC support ring	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
DSC shell	CO, SH, SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress Corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress Corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Galvanic corrosion	Loss of material	Localized Corrosion and Stress Corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Cover plates (outer)	CO, SH, SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Grapple ring and grapple support	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-3 Standardized Advanced NUHOMS dry shielded canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Grapple ring and grapple support	SR	Stainless steel	Sheltered	Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base walls, floor slab, roof; basemat; end and rear shield walls, corner shield wall; shielded ventilation air inlet plenum; inlet/outlet vents	SH, SR, TH*	Concrete	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperature	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base walls, floor slab, roof; basemat; end and rear shield walls, corner shield wall; shielded ventilation air inlet plenum; inlet/outlet vents	SH, SR, TH	Concrete	Air—outdoor	Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
			Sheltered	Aggressive chemical attack	Loss of strength	No	3.5.1.5
					Cracking	No	3.5.1.5
					Loss of material (spalling, scaling)	No	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperature	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10

Table 4-4 Standardized NUHOMS horizontal storage module							
Structure, System, or Component	**Intended Safety Function**	**Material**	**Environment**	**Aging Mechanism**	**Aging Effect**	**Aging Management**	**Technical Basis (Section)**
Reinforced concrete: base walls, floor slab, roof; basemat; end and rear shield walls, corner shield wall; shielded ventilation air inlet plenum; inlet/outlet vents	SH, SR, TH	Concrete	Sheltered	Freeze and thaw	Cracking	No	3.5.1.1
					Loss of material (spalling, scaling)	No	3.5.1.1
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	No	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
			Groundwater/soil	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base walls, floor slab, roof; basemat; end and rear shield walls, corner shield wall; shielded ventilation air inlet plenum; inlet/outlet vents	SH, SR, TH	Concrete	Groundwater/soil	Creep	Cracking	No	3.5.1.2
				Dehydration at high temperature	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Microbiological degradation	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.12
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.12
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.12
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.12
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base walls, floor slab, roof; basemat; end and rear shield walls, corner shield wall; shielded ventilation air inlet plenum; inlet/outlet vents	SH, SR, TH	Concrete	Groundwater/soil	Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
				Leaching of calcium hydroxide	Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
		Reinforcing steel	Air—outdoor; groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6
DSC support structure assembly hardware, base unit assembly hardware, module accessories	SR	Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
DSC support structure assembly hardware, base unit assembly hardware, module accessories	SR	Steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
DSC support structure assembly: support rail, rail extension plate and rail baseplate, plates, crossbeam, DSC stop plate extension	SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
DSC support structure assembly: support rail beams, support structure miscellaneous steel, plates, attachment/ installation hardware, DSC stop plate assembly, rail extension embedment, tube steel leg column	SR, TH	Steel	Sheltered	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
DSC support structure assembly: support rail plate	SR, TH	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
DSC axial retainer assembly: axial retainer, plate	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically Influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Cask restrain assembly: embedment assembly (rods, hex nuts, sleeve nuts), cask restraint embedment	SR	Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Cask restrain assembly: embedment assembly (rods, hex nuts, sleeve nuts), cask restraint embedment	SR	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
Heat shield assemblies: attachment hardware	SR	Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Heat shield assemblies: support structure, Z bracket, screw	SR	Stainless Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Heat shield assemblies: roof and side wall mounted heat shields, Z bracket	TH	Steel (galvanized)	Sheltered	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Heat shield assemblies: roof and side wall mounted heat shields/Z bracket, side heat shield fins, backing sheet, top louvered heat shield	TH	Aluminum	Sheltered	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.3.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.3.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.3.2
				Radiation embrittlement	Cracking	No	3.2.3.8
Heat shield assemblies: side heat shield, top heat shield	TH	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Shielded door assembly: door attachment hardware	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shielded door assembly: door attachment hardware	SR	Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Shielded door assembly: steel plates	SH, SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shielded door assembly: concrete core	SH, SR	Reinforced concrete, nonshrink grout or pea gravel or mortar mix	Fully encased (steel)	Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Cracking	No	3.5.1.13
					Loss of strength	No	3.5.1.13
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Radiation damage	Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
Inlet/outlet vents: outlet vent attachments	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inlet/outlet vents: liner plates	SH, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
Inlet/outlet vents: liner plates	SH, TH	Steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Shielded ventilation air inlet plenum	TH	Stainless steel (welded)	Air—outdoor	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Ventilation air outlet shielding blocks	TH	Stainless steel (welded)	Air—outdoor	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless Steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Ventilation air outlet shielding blocks	TH	Stainless Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Roof attachment assembly: angles, plates, dowel bar splicer	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Roof attachment assembly: roof attachment hardware	SR	Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Roof attachment assembly: roof attachment hardware	SR	Steel	Sheltered	Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
End and rear shield walls attachment hardware	SR	Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
HSM-to-HSM spacer channels	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
HSM-to-HSM spacer channels	SR	Steel	Air—outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
Dose reduction hardware: dose reduction assembly	SH	Steel	Air—outdoor	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Module-to-module connections	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Module-to-module connections	SR	Steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Lightning protection system	SR	Copper	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.5.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.5.3
				Pitting and crevice corrosion	Loss of material	No	3.2.5.2
				Radiation embrittlement	Cracking	No	3.2.5.4
Threaded fasteners and expansion anchors	SH, TH	Stainless Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-4 Standardized NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Threaded fasteners and expansion anchors	SH, TH	Stainless Steel	Air—outdoor	Stress relaxation	Loss of preload	No	3.2.2.10
Handrail	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base unit walls, floor slab, roof, top shield block, basemat, end and rear shield walls, corner shield wall, inlet/outlet vents	SH, SR, TH*	Concrete	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base unit walls, floor slab, roof, top shield block, basemat, end and rear shield walls, corner shield wall, inlet/outlet vents	SH, SR, TH	Concrete	Air—outdoor	Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
			Sheltered	Aggressive chemical attack	Loss of strength	No	3.5.1.5
					Cracking	No	3.5.1.5
					Loss of material (spalling, scaling)	No	3.5.1.5
				Creep	Cracking	No	3.5.1.2

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base unit walls, floor slab, roof, top shield block, basemat, end and rear shield walls, corner shield wall, inlet/outlet vents	SH, SR, TH	Concrete	Sheltered	Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	No	3.5.1.1
					Loss of material (spalling, scaling)	No	3.5.1.1
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	No	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base unit walls, floor slab, roof, top shield block, basemat, end and rear shield walls, corner shield wall, inlet/outlet vents	SH, SR, TH	Concrete	Groundwater/soil	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base unit walls, floor slab, roof, top shield block, basemat, end and rear shield walls, corner shield wall, inlet/outlet vents	SH, SR, TH	Concrete	Groundwater/ soil	Microbiological degradation	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.12
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.12
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.12
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.12
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: base unit walls, floor slab, roof, top shield block, basemat, end and rear shield walls, corner shield wall, inlet/outlet vents	SH, SR, TH	Reinforcing steel	Air—outdoor, groundwater	Leaching of calcium hydroxide	Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
				Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6
DSC support structure assembly hardware	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
DSC support structure assembly: support rail, rail extension plate, rail baseplate, stiffener plate, gusset plate, crossbeam, DSC stop plate extension	SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
DSC axial retainer assembly: axial retainer	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
DSC axial retainer assembly: axial retainer, plates	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
DSC axial retainer assembly: axial retainer, plates	SR	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Heat shield assemblies: attachment hardware	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
		Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Heat shield assemblies: attachment hardware	SR	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
Heat shield assemblies: side heat shield, top heat shield	TH	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Shielded door assembly: door attachment hardware	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shielded door assembly: door attachment hardware	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Shielded door assembly: backing plates	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
			Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shielded door assembly: backing plates	SR	Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Shielded door assembly: plates	SH, SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shielded door assembly: concrete core	SH, SR	Reinforced concrete, non-shrink grout or pea gravel or mortar mix	Embedded (steel or stainless steel)	Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Cracking	No	3.5.1.13
					Loss of strength	No	3.5.1.13
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
Inlet/outlet vents: outlet vent attachment hardware	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inlet/outlet vents: outlet vent attachment hardware	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Inlet/outlet vents: liner plates	SH, TH	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Roof attachment assembly: angles, plates, dowel bar splicer	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Roof attachment assembly: angles, plates, dowel bar splicer	SR	Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Roof attachment assembly: roof attachment hardware	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Roof attachment assembly: roof attachment hardware	SR	Stainless steel	Sheltered	Stress relaxation	Loss of preload	No	3.2.2.10
		Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
End and rear shield walls attachment hardware	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
End and rear shield walls attachment hardware	SR	Stainless steel	Sheltered	Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
		Steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
Module-to-module connection hardware	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-5 Standardized Advanced NUHOMS horizontal storage module

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Module-to-module connection hardware	SR	Stainless steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Structural shell (Cask body)	SH, SR, TH*	Steel	Embedded (neutron shielding)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel (welded)	Demineralized water	Stress corrosion cracking	Cracking	No	3.2.2.5
			Air — indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Embedded (neutron shielding)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Structural shell (Cask body)	SH, SR, TH	Stainless steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Inner shell (Cask body)	SH, SR, TH	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (Lead)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Top flange (Cask body)	SH, SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top flange (Cask body)	SH, SR	Stainless steel	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (neutron shielding)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Bottom support ring and bottom end forging (Cask body)	SH, SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom support ring and bottom end forging (Cask body)	SH, SR	Stainless steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (lead, neutron shielding)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Bottom end plate (Cask body)	SH, SR	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom end plate (Cask body)	SH, SR	Stainless steel	Embedded (stainless steel)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Lead gamma shielding (Cask body)	SH, TH	Lead	Embedded (steel, stainless steel)	None identified	None identified	No	3.2.6
Rails (Cask attachments)	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
Screw thread insert (Cask attachments)	SH, SR	Stainless steel	Embedded (stainless steel)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper trunnions (Cask attachments)	SH, SR	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
			Demineralized water	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Upper trunnion sleeves (Cask attachments)	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper trunnion sleeves (Cask attachments)	SH, SR	Steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
			Demineralized water	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper trunnion sleeves (Cask attachments)	SH, SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper trunnion cover plate and pad (Cask attachments)	SH, SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Upper trunnion nickel alloy (Cask attachments)	SR	Inconel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.4.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.4.3
				Stress corrosion cracking	Cracking	No	3.2.4.4
				Radiation embrittlement	Cracking	No	3.2.4.6
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.4.5
Upper and lower trunnion neutron shielding (Cask attachments)	SH, TH	Bisco NS-3	Embedded (steel, stainless steel)	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.3.1.2

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper and lower trunnion neutron shielding (Cask attachments)	SH, TH	Bisco NS-3	Embedded (steel, stainless steel)	Radiation embrittlement	Cracking	No	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Lower trunnions (Cask attachments)	SH, SR	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Lower trunnions sleeves (Cask attachments)	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lower trunnions sleeves (Cask attachments)	SH, SR	Steel	Air—indoor/outdoor	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
			Demineralized water	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lower trunnions sleeves (Cask attachments)	SH, SR	Stainless steel	Air—indoor/outdoor	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
Lower trunnion sleeve nickel alloy weld overlay (Cask attachments)	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lower trunnion sleeve nickel alloy weld overlay (Cask attachments)	SR	Stainless steel	Air—indoor/outdoor	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Internal sleeve components (Cask attachments)	SR	Aluminum	Embedded (stainless steel)	Radiation embrittlement	Cracking	No	3.2.3.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.3.6
Bottom head cap screw for internal sleeve (Cask attachments)	SR	Steel	Embedded (stainless steel, aluminum)	Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Stress relaxation	Loss of preload	No	3.2.1.10

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Washer for internal sleeve (Cask attachments)	SR	Stainless steel	Embedded (steel, stainless steel)	Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Spacer assembly (Cask attachments)	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Ram access penetration ring (Cask penetration)	SH, SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper and lower rings, outer shell relief valve support plates (Cask neutron shield)	SH, SR, TH	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
			Embedded (neutron shielding)	Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield panel support angles (Cask neutron shield)	SH, SR, TH	Stainless steel	Embedded (neutron shielding)	Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Neutron shield panels and plates (Cask neutron shield)	SH, SR, TH	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress.corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No.	3.2.2.9

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield panels and plates (Cask neutron shield)	SH, SR, TH	Stainless steel	Air—indoor/outdoor	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
			Embedded (neutron shielding)	Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Castable neutron shielding material (Cask neutron shield)	SH, TH	Bisco NS-3	Embedded (steel, stainless steel)	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.3.1.2
				Radiation embrittlement	Cracking	No	3.3.1.3

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Castable neutron shielding material (Cask neutron shield)	SH, TH	Bisco NS-3	Embedded (steel, stainless steel)	Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Inner, outer, and side top cover plates (Cask cover assembly)	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom cover plate (Cask cover assembly)	SH, SR, TH	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Top and bottom cover neutron shielding (Cask cover assembly)	SH	Bisco NS-3	Embedded (stainless steel)	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.3.1.2
				Radiation embrittlement	Cracking	No	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Bolts, screws, and washers for top and bottom cover plates (Cask cover assembly)	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bolts, screws, and washers for top and bottom cover plates (Cask cover assembly)	SH, SR	Steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Stress relaxation	Loss of preload	No	3.2.1.10
Socket head cap screws for bottom cover plate (Cask cover assembly)	SH, SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Stress relaxation	Loss of preload	No	3.2.2.10
Airflow wedge plates (Cask cover assembly)	SH, SR, TH	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2

Table 4-6 NUHOMS transfer cask							
Structure, System, or Component	**Intended Safety Function**	**Material**	**Environment**	**Aging Mechanism**	**Aging Effect**	**Aging Management**	**Technical Basis (Section)**
Airflow wedge plates (Cask cover assembly)	SH, SR, TH	Stainless steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
Support skid supplemental shielding	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
Bolts and washers for support skid supplemental shielding	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-6 NUHOMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bolts and washers for support skid supplemental shielding	SR	Steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Stress relaxation	Loss of preload	No	3.2.1.10
Upper and lower decon area cask shielding	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7

4.3 HI-STORM 100 and HI-STAR 100 systems

4.3.1 System description

Holtec International developed the HI-STORM (Holtec International–Storage and Transfer Operation Reinforced Module) 100 system and the HI-STAR (Holtec International–Storage, Transport, and Repository) 100 system. The HI-STORM 100 system consists of a metallic multipurpose canister (MPC) that contains the SNF assemblies, a vertical concrete storage overpack that contains the MPC during storage, and a HI-TRAC (Holtec International–Transfer Cask) TC that contains the MPC during loading, unloading, and transfer operations. The HI-STAR 100 system consists of an MPC and a vertical metal overpack, which is used to load, unload, transfer, and store the SNF assemblies contained in the MPC. The HI-STORM 100 system is certified only for storage, while the HI-STAR 100 system (including its metal overpack) is certified for both storage and transportation. Figure 4-9 presents schematics of the HI-STORM 100 and HI-STAR 100 systems.

The HI-STORM design is presently licensed for use in the United States under NRC Docket 72-1014, in combination with the MPC-24, MPC-32, and MPC-68 canisters, while the HI-STAR design is licensed for use under NRC Docket 72-1008, with the MPC-24 and MPC-68 canisters. As in the case for the NUHOMS DSCs, the names of the Holtec MPCs reflect the number of fuel assemblies each MPC can hold. In addition, a variant design of the HI-STAR overpack, designated HI-STAR HB, is being used in conjunction with the MPC-HB canister under a site-specific license at the Humboldt Bay ISFSI. The details of the components of the two storage systems are provided below.

4.3.2 Multipurpose canister

The MPCs are welded cylindrical structures with an identical outer diameter, so that any MPC will fit into either the HI-STORM or HI-STAR overpacks. However, only certain MPC and overpack combinations are currently licensed for use. Each MPC is an assembly consisting of a honeycombed fuel basket, baseplate, canister shell, lid, and closure ring. A cross sectional elevation view of a fuel basket for the MPC-68 series is shown in Figure 4-10. The number of spent fuel storage locations in each of the MPCs depends on the SNF assembly characteristics.

Ten MPC models, distinguished by the type and number of SNF assemblies authorized for loading, are presently certified by the NRC for use in the United States. These are the MPC-24 series (including the MPC-24E and MPC-24EF), the MPC-32 series (including the MPC-32F), and the MPC-68 series (including the MPC-68F, MPC-68FF, MPC-68M, and MPC-HB), shown in cross sectional views in Figure 4-11. The numerical suffix for each canister series denotes the maximum number of fuel elements that it can accommodate. Those canisters with “E” and “F” designations are designed for the storage of damaged fuel rods and fuel debris. The MPC-68M design contains a fuel basket constructed of Metamic-HT™, a neutron absorbing material that also has a structural function.

The fuel storage cells in the MPC-24 series are physically separated from one another by a water gap, also called a flux trap, for criticality control. Flux traps are not used in the MPC-32 and MPC-68 series. The MPC-32 design includes credit for soluble boron in the MPC water during wet fuel loading and unloading operations for criticality control. The MPC fuel basket is positioned and supported within the MPC shell by a set of basket supports welded to the inside of the MPC shell. In the early-vintage MPCs that were loaded under the original HI-TORM 100 design, optional heat conduction elements (fabricated from thin aluminum Alloy 1100) may have

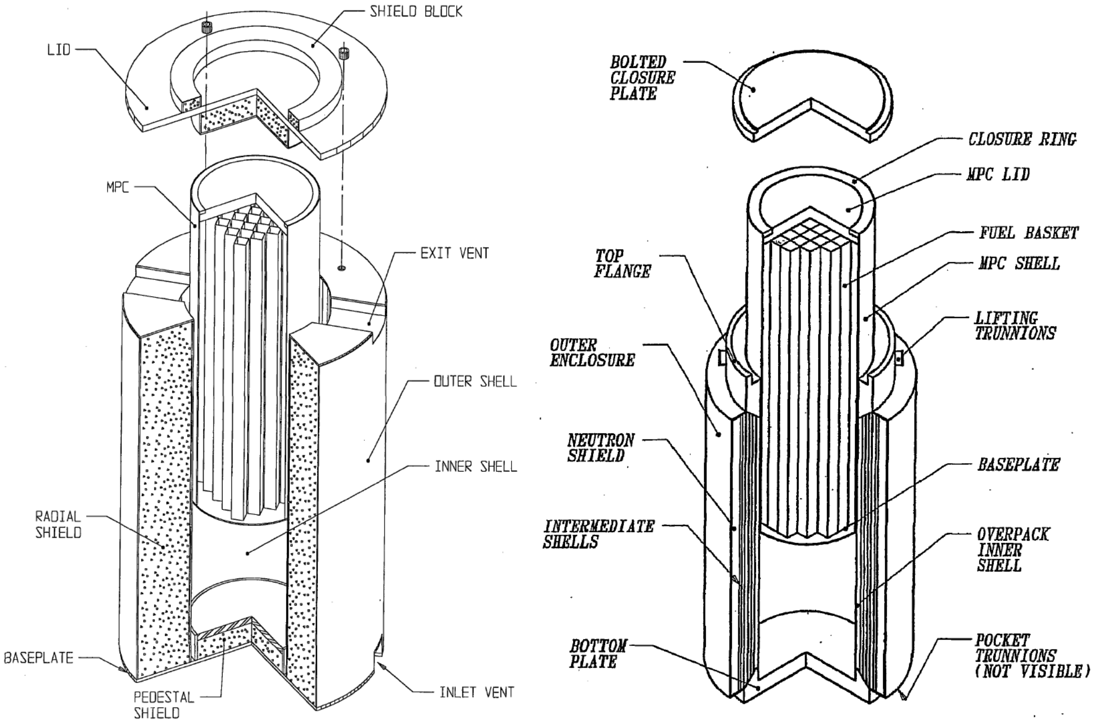


Figure 4-9 HI-STORM 100 (left) (Holtec International, 2013) and HI-STAR 100 (right) (Holtec International, 2001) systems

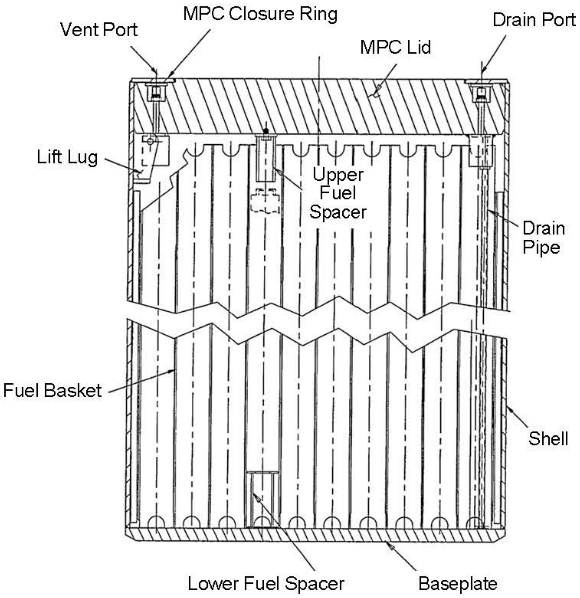
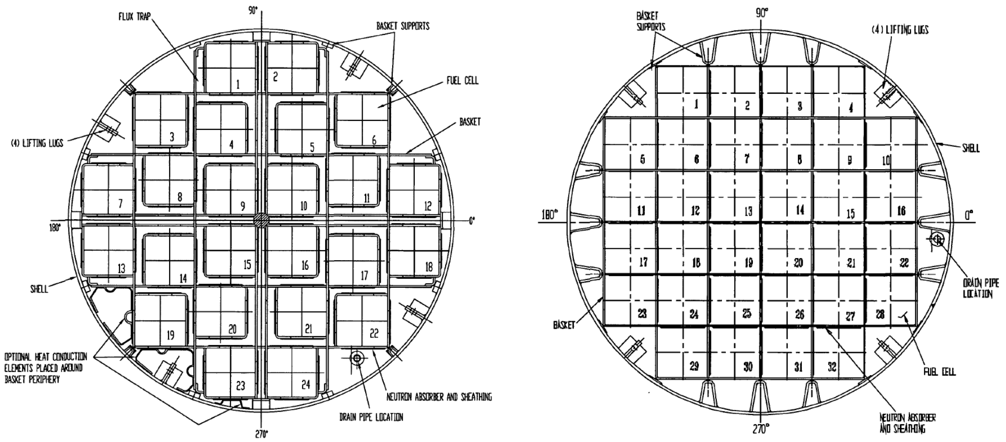
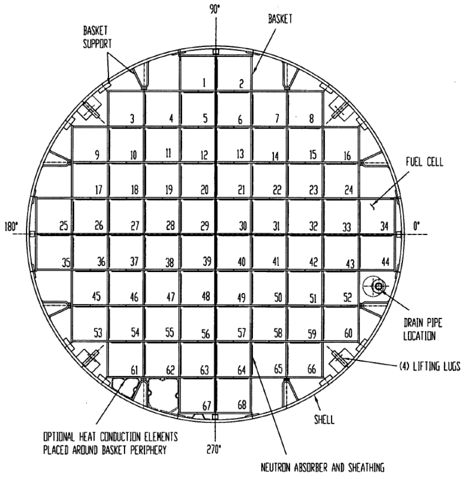


Figure 4-10 Cross section elevation view of MPC (Holtec International, 2013)



(a) MPC-24/24E/24EF

(b) MPC-32/32F



(c) MPC-68/68F/68FF

Figure 4-11 Cross sectional views of different MPC designs (Holtec International, 2013)

been installed between the periphery of the basket, the MPC shell, and the basket supports. For shorter SNF assemblies, upper and lower fuel spacers, as appropriate, maintain the axial position of the SNF assembly within the MPC basket.

All structural components in MPCs are made of a material designated by the manufacturer as Alloy X. Candidate Alloy X materials include Types 304, 304LN, 316, and 316LN austenitic stainless steels. All MPC components that are likely to come in contact with spent fuel pool water or the ambient environment are constructed from stainless steel, with the exception of neutron poison plates, aluminum seals on vent and drain port caps, and optional aluminum heat conduction elements.

Lifting lugs attached to the inside surface of the MPC canister shell (shown in Figure 4-10) permit placement of the empty MPC into the HI-TRAC transfer cask and also serve to axially locate the MPC lid before welding. They are not used to handle a loaded MPC, because the MPC lid is installed before any handling of a loaded canister.

The top end of the MPC incorporates a redundant closure system. The MPC lid is a circular plate (fabricated from one piece or two pieces—split top and bottom) that is welded to the MPC outer shell. In the two-piece lid design, only the top piece comprises a part of the enclosure vessel's pressure boundary; the bottom piece is attached to the top piece with a nonstructural, nonpressure-retaining weld and acts as a radiation shield. The lid is equipped with vent and drain ports that are used to remove moisture and air from the MPC and backfill the MPC with helium. The vent and drain ports are covered and seal-welded before the closure ring is installed. The closure ring is a circular ring edge-welded to the MPC shell and lid. The MPC lid provides sufficient rigidity to allow the entire MPC, loaded with spent nuclear fuel, to be lifted by the threaded holes in the MPC lid.

Boral® and METAMIC™ neutron poison panels are used in the basket and are enclosed in Alloy X stainless steel sheathing that is stitch-welded to the MPC basket cell walls along their entire periphery. Thus, the neutron poison material is contained in a tight, welded pocket enclosure. The shear strength of the pocket weld joint, which is an order of magnitude greater than the weight of a fuel assembly, ensures that the neutron poison and its enveloping sheathing pocket will maintain their as-installed position under all loading, storage, and transport conditions. In addition, the pocket joint detail ensures that fuel assembly insertion or withdrawal into or out of the MPC basket will not lead to a disconnection of the sheathing from the cell wall.

The MPC does not require any valves, gaskets or mechanical seals for confinement. Figure 4-12 shows the MPC confinement boundary. All components of the confinement boundary are safety significant and are fabricated entirely of stainless steel. The primary confinement boundary is defined by the outline formed by the sealed, cylindrical enclosure of the MPC shell (including any associated axial or circumferential welds) welded to the baseplate at the bottom, the MPC lid welded around the top circumference to the shell wall, and the port cover plates welded to the lid. A shield lid is bolted to the top of the MPC lid and provides radiation shielding.

The helium backfill gas plays an important role in the MPC thermal performance. It fills all the spaces between solid components and provides an improved conduction medium relative to air for dissipating decay heat in the MPC. Furthermore, the pressurized helium environment within the MPC sustains a closed-loop thermo-siphon action, removing SNF decay heat by upward flow of helium through the storage cells.

Table 4-7 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the MPC. The AMPs that provide an acceptable approach to managing the aging effects are also identified in the table.

4.3.3 HI-STORM concrete overpack

The HI-STORM overpacks are thick-walled concrete cylindrical vessels enclosed in a steel shell. There are three base HI-STORM overpack designs: (i) HI-STORM 100, (ii) HI-STORM 100S, and (iii) HI-STORM 100S Version B. *The significant differences among the three are overpack height, MPC pedestal height, location* of the air outlet ducts, and vertical alignment of the inlet and outlet air ducts. The HI-STORM 100S Version B overpack design does not include a concrete-filled pedestal to support the MPC. Instead, the MPC rests upon a steel plate that maintains the MPC sufficiently above the inlet air ducts to prevent direct radiation shine through the ducts. Figure 4-13 shows cross sectional views of the HI-STORM 100 and 100S overpacks. The HI-STORM 100A and 100SA overpack designs are the anchored variant of the HI-STORM 100 and 100S designs.

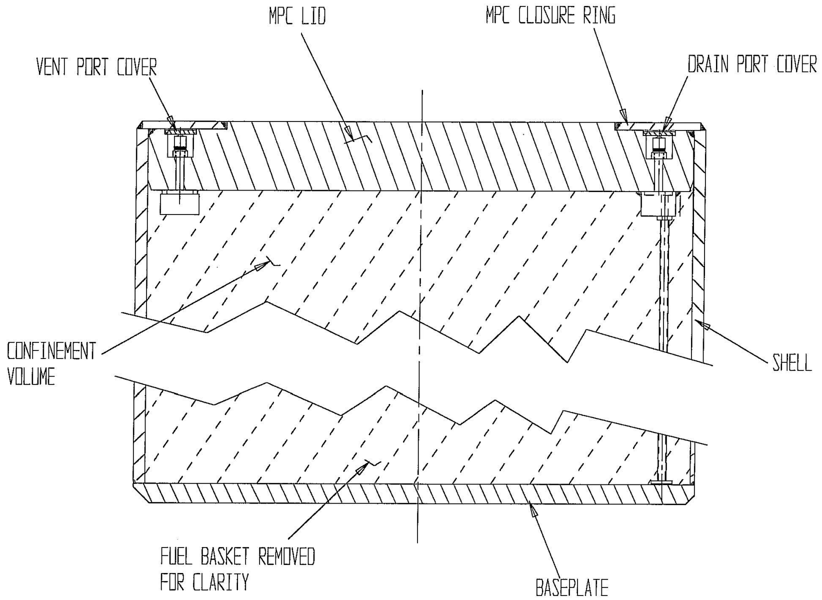


Figure 4-12 MPC confinement boundary (Holtec International, 2013)

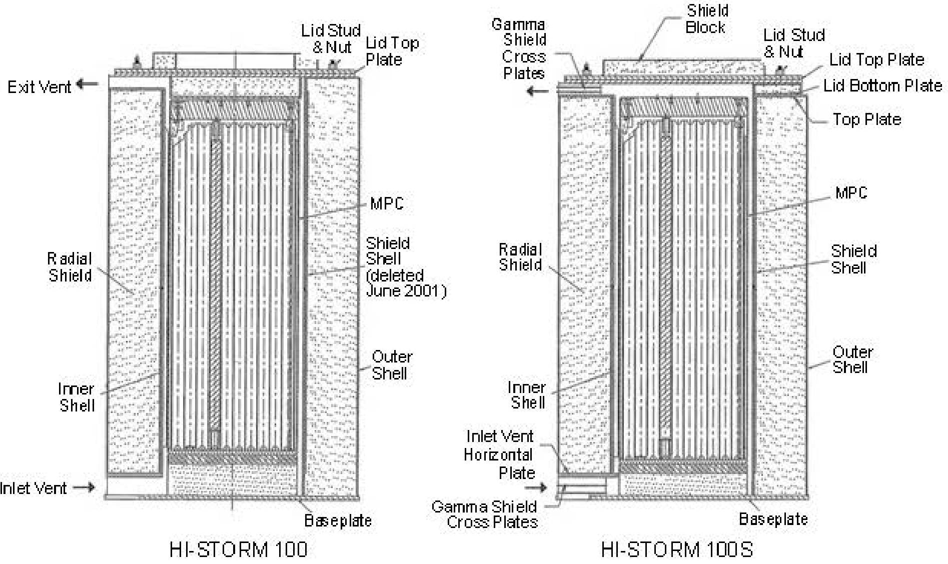


Figure 4-13 Cross sectional views of the HI-STORM 100 and 100S overpacks with an MPC inserted (Holtec International, 2013)

A base HI-STORM overpack design is capable of storing each type of MPC. The overpack inner shell is provided with channels distributed around the inner cavity that provide guidance for MPC insertion and removal, and a flexible medium to absorb some of the impact during a tipover. They also allow the flow of cooling air through the overpack. The main structural function of the HI-STORM overpack is provided by carbon steel, and the main shielding function is provided by concrete. The concrete, enclosed by cylindrical inner and outer steel shells, a thick baseplate, and a top plate, is specified to provide the necessary shielding properties and compressive strength. The overpack lid has appropriate concrete shielding to provide neutron and gamma attenuation in the vertical direction.

The HI-STORM overpack has air ducts to allow for passive natural convection cooling of the contained MPC. A minimum of four air inlets and four air outlets are located at the lower and upper extremities of the storage system, respectively. The vertical annulus between the MPC and the inner shell of the overpack facilitates an upward flow of air by buoyancy forces, drawing ambient air from the inlet vents and releasing it from the outlet vents at the top of the HI-STORM storage system. The annulus ventilation flow cools the hot MPC surfaces and transfers decay heat to the outside environment.

The principal function of the concrete is to provide shielding against gamma and neutron radiation. However, it also imparts a large thermal inertia to the HI-STORM overpack, allowing it to moderate the rise in temperature of the system under hypothetical conditions when all ventilation passages are assumed to be blocked. The high thermal inertia characteristics of the HI-STORM concrete also control the temperature of the MPC in the event of a postulated fire accident at the ISFSI. Although the annular concrete mass in the overpack shell is not a structural member, it does act as an elastic/plastic filler of the intershell space.

Four threaded anchor blocks, located at 90-degree intervals around the circumference of the top of the overpack lid, are provided for lifting. The anchor blocks are integrally welded to the radial plates, which in turn are full-length welded to the overpack inner shell, outer shell, and baseplate (HI-STORM 100) or the inlet air duct horizontal plates (HI-STORM 100S).

The HI-STORM 100S Version B overpack design incorporates partial-length radial plates at the top of the overpack to secure the anchor blocks and uses both gussets and partial-length radial plates at the bottom of the overpack for structural stability. The overpack may also be lifted from the bottom using specially designed lifting transport devices, including hydraulic jacks, air pads, Hillman rollers, or other designs based on site-specific needs and capabilities.

For anchoring, the HI-STORM 100A overpack baseplate is extended to allow it to be attached to the reinforced concrete structure of the ISFSI. Sector lugs are bolted to the ISFSI pad using anchor studs. The lateral load-bearing capacity of the HI-STORM/pad interface is many times greater than the horizontal sliding force exerted on the cask under the postulated design-basis earthquake seismic event. Thus, the potential for lateral sliding of the HI-STORM 100A system during a seismic event is precluded, as is the potential for any bending action on the anchor studs.

The HI-STORM 100 system also includes a variant 100U underground module design. The HI-STORM 100U design provides storage of an MPC inside a cylindrical cavity located entirely below the top of the grade of the ISFSI. HI-STORM 100U comprises the cavity enclosure container, consisting of the container shell welded to the bottom plate and the container flange, and the closure lid, divider shell, insulation, and bearing pads, as well as the interfacing and proximate structures, such as interface pad, support foundation pad, subgrade surrounding the module, top surface pad, and retaining wall.

Table 4-8 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the HI-STORM overpack, respectively. The AMPs that provide an acceptable approach to managing the aging effects are also identified in the tables.

4.3.4 HI-STAR metal overpack

The HI-STAR 100 overpack is a sealed, thick-walled carbon and low-alloy steel cylindrical vessel. The overpack containment boundary is formed by an inner shell welded at the bottom to a cylindrical main flange and bolted to a top closure plate. The HI-STAR 100 overpack with the MPC partially inserted is shown in Figure 4-9. The overpack consists of one inner shell, five intermediate shells, and one enclosure shell, which form the body of the overpack. Figure 4-14 and Figure 4-15 provide an elevation and cross section view, respectively, of the overpack.

Two concentric grooves are machined into the closure plate to accept the metallic seals. The bolted closure plate is recessed into the top flange, and the bolted joint is configured to provide maximum protection to the closure bolts and seals in the event of a drop accident. The closure plate has test and vent ports, which are sealed by a threaded port plug with a metallic seal. The bottom plate has a drain port that is sealed by a threaded port plug with a metallic seal. The inner surfaces of the HI-STAR overpack form an internal cylindrical cavity for housing the MPC.

The outer surface of the overpack inner shell is buttressed with the five layers of intermediate shells of gamma shielding in the form of layers of carbon steel plate installed so as to ensure a permanent state of contact between adjacent layers. Besides serving as an effective gamma shield, these intermediate layers provide additional strength to the overpack to resist potential punctures or penetrations from external missiles. Radial channels are vertically welded to the outside surface of the outermost intermediate shell at equal intervals around the circumference (see Figure 4-15). The radial channels act as fins for improved heat conduction to the overpack outer enclosure shell surface and as cavities for retaining and protecting the Holtite-A™ neutron shield described below.

The outer enclosure shell is formed by welding enclosure shell panels between each pair of radial channels to form the neutron shielding cavities, as shown in Figure 4-15. At the top of the outer enclosure shell, rupture disks are positioned in a recessed area. These rupture disks relieve internal pressure that may develop as a result of a fire accident and subsequent off gassing of the neutron shield material. Within each radial channel, a layer of silicone sponge is positioned to act as a thermal expansion foam to compress as the neutron shield expands.

The exposed steel surfaces of the overpack are painted to prevent corrosion. Lifting trunnions are attached to the overpack top flange forging for lifting and for rotating the cask body between vertical and horizontal positions. The lifting trunnions are located 180 degrees apart in the sides of the top flange. Pocket trunnions are welded to the lower side of the overpack to provide a pivoting axis for rotation. The lifting trunnions do not protrude beyond the cylindrical envelope of the overpack enclosure shell. This feature reduces the potential for a direct impact on a trunnion in the event of an overpack side impact. The overpack is provided with aluminum honeycomb impact limiters, one at each end, to ensure that the impact loadings during accident conditions are maintained below the design levels. The neutron shielding material used in the HI-STAR 100 overpack is Holtite-A™, a poured-in-place solid borated synthetic neutron-absorbing polymer.

Table 4-9 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the HI-STAR overpack. The AMPs that provide an acceptable approach to managing the aging effects are also identified in the table.

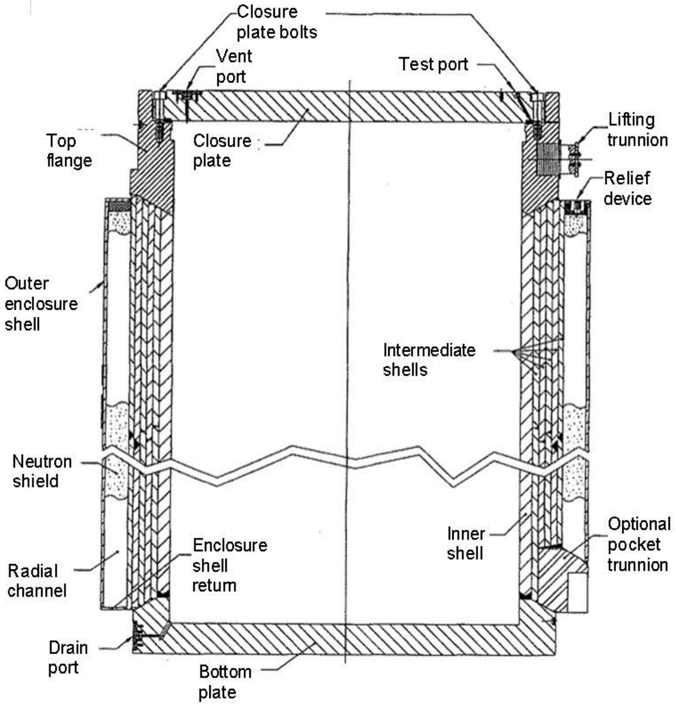


Figure 4-14 HI-STAR 100 overpack elevation view (Holtec International, 2001)

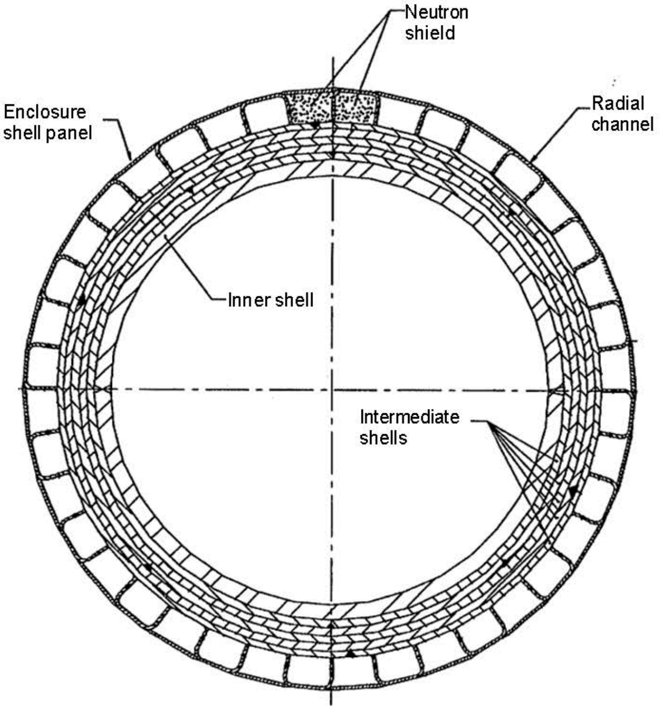


Figure 4-15 HI-STAR 100 overpack cross sectional view (Holtec International, 2001)

1

4.3.5 Transfer cask

The HI-TRAC TC is a heavy-walled carbon steel cylindrical vessel composed of an inner shell and an outer shell with lead in between to provide gamma shielding (Holtec International, 2013). The TC also includes an exterior carbon steel water jacket for neutron shielding. There are four basic HI-TRAC TC designs: two standard designs, which are a 125-ton HI-TRAC 125 and a 100-ton HI-TRAC 100, and two optional designs with a dual-purpose lid for loading and transfer operations, which are the 125-ton HI-TRAC 125D and the 100-ton HI-TRAC 100D. Figure 4-16 shows the cross section of a standard HI-TRAC 125 TC with both a pool lid and a transfer lid attached. Since all the MPCs have the same outer diameter, the inner diameter of all HI-TRAC TCs is the same. However, the external dimensions of the HI-TRAC TCs are different, because the 100-ton TCs have a reduced thickness of lead and water shielding.

The main structural function of the HI-TRAC TCs is provided by carbon steel, and the main neutron and gamma shielding functions are provided by water and lead, respectively. The top lid of the HI-TRAC 125 and HI-TRAC 125D TCs contains additional Holtite-A™ neutron shielding material. The MPC access hole through the HI-TRAC top lid allows the lowering or raising of the MPC between the TC and the overpack.

The standard design HI-TRAC TCs (including HI-TRAC 100 and HI-TRAC 125) include two bottom lids (pool lid and transfer lid). The pool lid is bolted to the bottom flange of the HI-TRAC and is used during MPC fuel loading and sealing operations. In addition to providing shielding in the axial direction, the pool lid incorporates two gasket seals, one between the pool lid top and the bottom flange and the other between the MPC outer wall and the TC inner wall close to the top lid of the TC. These seals provide a barrier from contamination of the exterior of the MPC by the spent fuel pool water. After the MPC has been drained, dried, and sealed, the pool lid is removed and the transfer lid is attached. The transfer lid incorporates two sliding doors that allow the opening of the HI-TRAC bottom for the MPC to be raised or lowered. Unlike the standard designs, the HI-TRAC 100D and HI-TRAC 125D TCs do not require swapping the pool lid for a transfer lid to facilitate transfer of the MPC. The HI-STORM mating device is used to remove the pool lid during MPC transfer operations.

In the standard designs, the HI-TRAC TC is equipped with two lifting trunnions located below the top flange and two pocket trunnions located above the bottom flange. The lifting trunnions, made of nickel alloy or stainless steel, are used to vertically handle the HI-TRAC TC. The carbon steel pocket trunnions provide a pivot point for the rotation of the HI-TRAC TC for downending or upending the HI-TRAC TC with a loaded MPC. The HI-TRAC 100D and HI-TRAC 125D TCs are equipped with only lifting trunnions.

Table 4-10 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the HI-TRAC TC. The AMPs that provide an acceptable approach to managing the aging effects are also identified in the table.

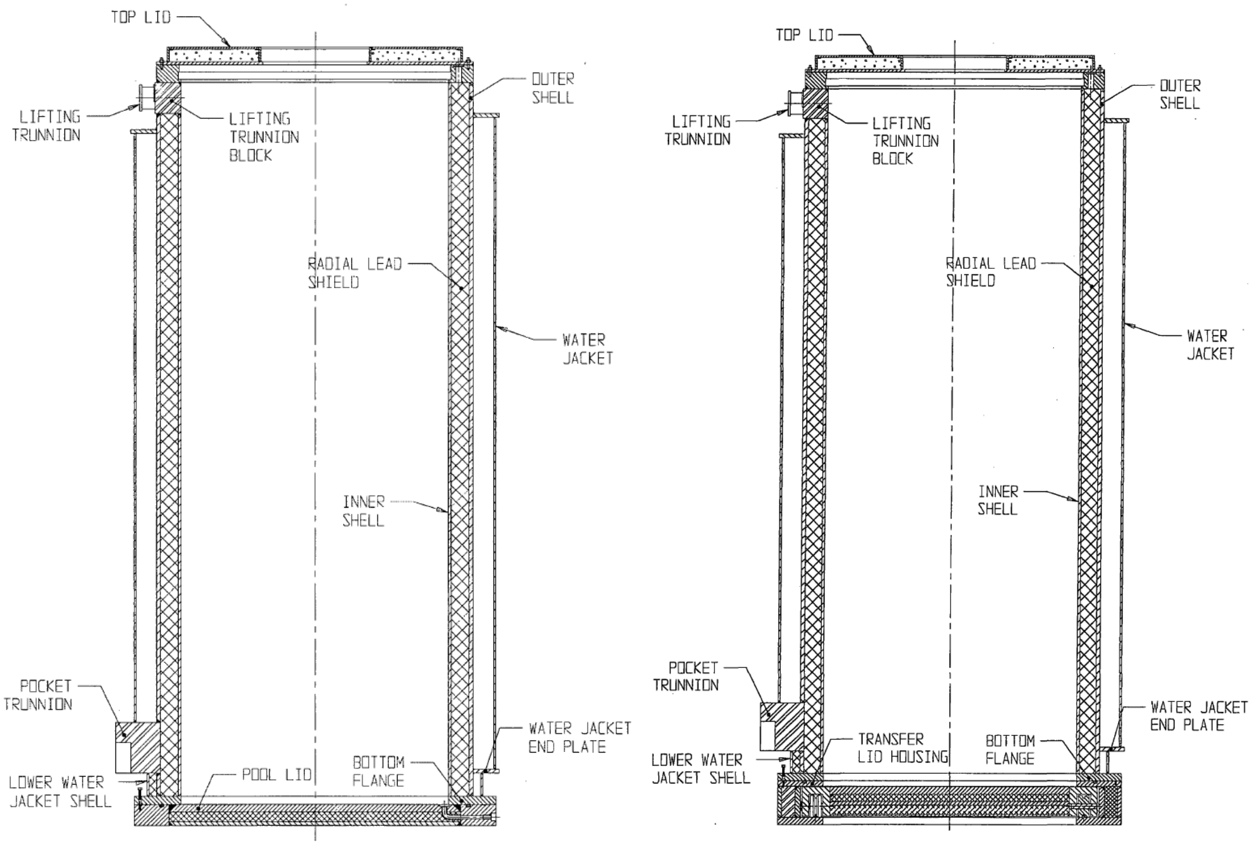


Figure 4-16 Cross sectional views of the HI-TRAC 125 transfer cask with pool lid (left) and transfer lid (right) (Holtec International, 2013)

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shell	CO, SH, SR, TH*	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Baseplate	CO, SH, SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Baseplate	CO, SH, SR, TH	Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Lid	CO, SH, SR, TH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid	CO, SH, SR, TH	Stainless steel	Sheltered	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Closure ring	CO	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Port cover plates	CO	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Port cover plates	CO	Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Basket cell plates	CR, SH, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
BWR fuel basket	CR, SH, SR, TH	Metamic-HT™	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6
				General corrosion	Loss of material	No	3.4.2.1
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7
Neutron absorber	CR, SH, TH	Boral®	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron absorber	CR, SH, TH	Boral®	Helium	Wet corrosion and blistering	Change in dimensions	No	3.4.2.3
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7
		Metamic™	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
				Thermal aging	Loss of strength	No	3.4.2.6
				General corrosion	Loss of material	No	3.4.2.1
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.2.7
Drain and vent shield blocks	SH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Bottom portion of two-piece lid	SH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom portion of two-piece lid	SH	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
		Steel coated with stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
				General corrosion	Loss of material	No	3.2.2.1
Sheathing	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Basket supports	SR, CR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lifting lugs	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Lifting lug base plate	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Upper fuel spacer column	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Upper fuel spacer end plate	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-7 HI-STORM / HI-STAR multipurpose canister							
Structure, System, or Component	**Intended Safety Function**	**Material**	**Environment**	**Aging Mechanism**	**Aging Effect**	**Aging Management**	**Technical Basis (Section)**
Lower fuel spacer column	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Lower fuel spacer end plate	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Vent shield block spacer	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Vent and drain tubes	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-7 HI-STORM / HI-STAR multipurpose canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Damaged fuel container	SR, CO	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Threaded disc, plug adjustment	CO	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Vent and drain plugs	CO	Aluminum	Helium	Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				General corrosion	Loss of material	No	3.2.3.1
				Radiation embrittlement	Cracking	No	3.2.3.8

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shield: radial shield, shield block, pedestal shield, lid shield	SH*	Concrete	Fully encased (steel)	Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Cracking	No	3.5.1.13
					Loss of strength	No	3.5.1.13
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9
				Reaction with aggregates	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.3
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.3
Shield block (base, ring, shell)	SH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid inner ring	SR	Steel	Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Lid outer ring	SH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Shield shell	SH	Steel	Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Gamma shield cross plates	SH	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
			Air—outdoor	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
			Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Gamma shield cross plates	SH	Stainless steel	Air—outdoor	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Baseplate, base spacer block	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Outer shell	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Outer shell	SR	Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Inner shell, lid bottom plate, and lid shell	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Pedestal shell	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-8 HI-STORM 100 overpack							
Structure, System, or Component	**Intended Safety Function**	**Material**	**Environment**	**Aging Mechanism**	**Aging Effect**	**Aging Management**	**Technical Basis (Section)**
Pedestal platform, MPC support	SH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Inlet/outlet vent, vertical and horizontal plates, top plate, lid top plate, shear ring	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Heat shield, heat/lid shield ring	TH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Heat shield, heat/lid shield ring	TH	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Radial plate, radial gusset	SR	Steel	Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Lid stud and nut, lid closure bolt	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Lid stud	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid washer	SR	Stainless steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Bolt anchor block	SR	Steel	Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Channel	SR	Steel (galvanized)	Sheltered	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel (welded)	Sheltered	Atmospheric stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2

Table 4-8 HI-STORM 100 overpack							
Structure, System, or Component	**Intended Safety Function**	**Material**	**Environment**	**Aging Mechanism**	**Aging Effect**	**Aging Management**	**Technical Basis (Section)**
Channel	SR	Stainless steel	Sheltered	Radiation embrittlement	Cracking	No	3.2.2.9
Channel mounts	SR	Steel	Sheltered	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid lift block	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Lug support ring, gusset	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lug support ring, gusset	SR	Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Stud with nut	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Closure lid concrete (HI-STORM 100U)	SH	Concrete	Fully-encased (steel)	Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Closure lid concrete (HI-STORM 100U)	SH	Concrete	Fully-encased (steel)	Reaction with aggregates	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.3
				Reaction with aggregates	Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.3
Closure lid steel (HI-STORM 100U)	SH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Container shell, bottom plate (HI-STORM 100U)	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Groundwater/soil	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	General corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (steel)	Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Container flange (HI-STORM 100U)	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Divider shell and divider shell restraints (HI-STORM 100U)	TH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Upper and lower MPC guides (HI-STORM 100U)	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
MPC bearing pads (HI-STORM 100U)	SR	Steel (with stainless steel liners)	Sheltered	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Insulation (HI-STORM 100U)	TH	Kaowool (ceramic fiber) or equivalent	Fully encased (steel)	Moisture absorption	Loss of insulation efficiency (increasing thermal conductivity)	No	3.5.2
				Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.5.2
Reinforced concrete: VVM interface pad, top surface pad (HI-STORM 100U)	SR, SH	Concrete	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: VVM interface pad, top surface pad (HI-STORM 100U)	SR, SH	Concrete	Air—outdoor	Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: VVM interface pad, top surface pad (HI-STORM 100U)	SR, SH	Concrete	Air—outdoor	Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
			Groundwater/soil	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: VVM interface pad, top surface pad (HI-STORM 100U)	SR, SH	Concrete	Groundwater/soil	Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Microbiological degradation	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.12
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.12
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.12
				Microbiological degradation	Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.12
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: VVM interface pad, top surface pad (HI-STORM 100U	SR, SH	Concrete	Groundwater/soil	Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
		Reinforcing steel	Air - outdoor; groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6
Retaining wall, support foundation pad (HI-STORM 100U)	SR, SH	Concrete	Groundwater/soil	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Retaining wall, support foundation pad (HI-STORM 100U)	SR, SH	Concrete	Groundwater/soil	Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	No	3.5.1.1
					Loss of material (spalling, scaling)	No	3.5.1.1
				Microbiological degradation	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.12
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.12
				Microbiological degradation	Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.12
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.12
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9

Table 4-8 HI-STORM 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Retaining wall, support foundation pad (HI-STORM 100U)	SR, SH	Concrete	Groundwater/soil	Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	No	3.5.1.14
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
		Reinforcing steel	Air - outdoor; groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inner shell	CO, SH*	Steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Bottom plate	CO, SH, SR	Steel	Air—outdoor	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Top flange	CO, SH, SR	Steel	Air—outdoor	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top flange	CO, SH, SR	Steel	Air—outdoor	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Closure plate	CO, SH, SR	Steel	Air—outdoor	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Closure plate	CO, SH, SR	Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Closure plate bolts	CO, SR	Nickel alloy	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.4.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.4.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.4.3
				Pitting and crevice corrosion	Loss of material	No	3.2.4.2
				Radiation embrittlement	Cracking	No	3.2.4.6
				Stress relaxation	Loss of preload	No	3.2.4.6
Port plug	CO	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Port plug seal and port cover seal	CO	Nickel alloy	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.4.3
				Pitting and crevice corrosion	Loss of material	No	3.2.4.2
				Radiation embrittlement	Cracking	No	3.2.4.6
Closure plate seals	CO	Nickel alloy	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.4.3
				Pitting and crevice corrosion	Loss of material	No	3.2.4.2
				Radiation embrittlement	Cracking	No	3.2.4.6
Intermediate shells	SH, SR	Steel	Embedded (Holtite-A™)	Radiation embrittlement	Cracking	No	3.2.1.9
Neutron shield	SH	Holtite-A™	Embedded (steel)	Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Removable shear ring	SH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Pocket trunnion plug plate	SH	Stainless steel (welded)	Air—outdoor	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Radial channels	SR, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (Holtite-A™)	Radiation embrittlement	Cracking	No	3.2.1.9
Pocket trunnion	SH	Stainless steel (welded)	Air—outdoor	Stress corrosion cracking	Cracking	External Surfaces Monitoring of Metallic Components AMP	3.2.2.5
		Stainless steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Pocket trunnion	SH	Stainless steel	Air—outdoor	Pitting and crevice corrosion	Loss of material (precursor to stress corrosion cracking)	External Surfaces Monitoring of Metallic Components AMP	3.2.2.2
				Radiation embrittlement	Cracking	No	3.2.2.9
Lifting trunnion	SR	Nickel alloy	Air—outdoor	Atmospheric stress-corrosion cracking	Cracking	No	3.2.4.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.4.3
				Pitting and crevice corrosion	Loss of material	No	3.2.4.2
				Radiation embrittlement	Cracking	No	3.2.4.6
Rupture disk	SR	Brass	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.5.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.5.3
				Pitting and crevice corrosion	Loss of material	No	3.2.5.2
				Radiation embrittlement	Cracking	No	3.2.5.4
Rupture disk plate	SR	Steel	Air—outdoor	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Rupture disk plate	SR	Steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Removable shear ring bolt, pocket trunnion plug screw, and alignment pin	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Enclosure shell panels and enclosure shell return	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Enclosure shell panels and enclosure shell return	SR	Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (Holtite-A™)	Radiation embrittlement	Cracking	No	3.2.1.9
Port cover	SR	Steel	Air—outdoor	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Port cover bolt	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Port cover bolt	SR	Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Trunnion locking pad and end cap bolts	SR	Steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.1.5
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Lifting trunnion end cap and locking pad	SR	Steel	Air—outdoor	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-9 HI-STAR 100 overpack

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lifting trunnion end cap and locking pad	SR	Steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Outer shell	SH, SR, TH*	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically Influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9
			Demineralized water or 25% ethylene glycol solution	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Inner shell	SH, SR, TH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Radial ribs	SH, SR, TH	Steel	Demineralized water or 25% ethylene glycol solution	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Radial lead shield	SH, TH	Lead—ASTM B29	Embedded (steel)	None identified	None identified	No	3.2.5.4
Water jacket enclosure shell panels	SH, SR, TH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Demineralized water or 25% ethylene glycol solution	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Lower water jacket shell	SH, SR, TH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lower water jacket shell	SH, SR, TH	Steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Demineralized water or 25% ethylene glycol solution	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Water jacket end plate, short rib	SH, SR, TH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Demineralized water or 25% ethylene glycol solution	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice Corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Pool lid outer ring	SH, SR, TH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Pool lid outer ring	SH, SR, TH	Steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Pool lid top and bottom plates	SH, SR, TH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Pool lid bolt	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Pool lid lead shield	SH, TH	Lead	Embedded (steel)	None identified	None identified	No	3.2.5.4
Top flange	SR, SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top flange	SR, SH	Steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Top lid outer and inner rings, top and bottom plates, lifting block	SR, SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (Holtite-A™)	Radiation embrittlement	Cracking	No	3.2.1.9
Top lid stud or bolt	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Top lid nut	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top lid nut	SR	Steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Top lid shielding	SH, TH	Holtite-A™	Embedded (steel)	Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Fill port plugs	SR, SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9
Lifting trunnion block	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lifting trunnion block	SR	Steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
Lifting trunnion	SR	Nickel alloy	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.4.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.4.3
				Stress corrosion cracking	Cracking	No	3.2.4.4
				Radiation embrittlement	Cracking	No	3.2.4.6
				Wear	Loss of material	Transfer Casks AMP	3.2.4.8
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
Lifting trunnion end cap	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lifting trunnion end cap	SR	Steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
Pocket trunion, removable pocket trunion, pocket trunnion base	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Dowel pins, pocket trunnion bolts	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Bottom flange	SR, SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation Embrittlement	Cracking	No	3.2.1.9

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Transfer lid top, bottom, intermediate, cover, and cover side plates	SR, SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Transfer lid door top, middle, bottom, interface, side, and end plates	SR, SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Transfer lid door top, middle, and side plates	SR, SH	Steel	Embedded (Holtite-A™)	Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9
Transfer lid door wheel housing	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Transfer lid door wheel housing	SR	Steel	Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (Holtite-A™)	Radiation embrittlement	Cracking	No	3.2.1.9
Transfer lid wheel shaft	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Transfer lid housing stiffener	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Transfer lid door lock bolt	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Transfer lid door lock bolt	SR	Steel	Air—indoor/outdoor	Stress relaxation	Loss of preload	No	3.2.1.10
Transfer lid lifting lug, lug pad	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
Transfer lid wheel track	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
Transfer lid door stop block	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation Embrittlement	Cracking	No	3.2.1.9

Table 4-10 HI-TRAC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Transfer lid door stop block bolt	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.4
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.2
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Transfer lid door shielding	SH, TH	Holtite-A™	Embedded (steel)	Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Transfer lid door lead shield	SH, TH	Lead	Embedded (steel)	None identified	None identified	No	3.2.5.4
Transfer lid side lead shield	SH, TH	Lead	Embedded (steel)	None identified	None identified	No	3.2.5.4

4.4 TN-32 and TN-68 systems

4.4.1 System description

The Transnuclear Inc. (TN) spent-fuel storage cask is a vertical metal cask with a bolted lid closure and two metallic O-rings forming the seal. As a storage cask, it provides confinement, shielding, criticality control, and passive heat removal. There are three types of TN metal storage casks: TN-32, TN-40 (TN-40HT), and TN-68. Only the TN-32 (NRC Docket 72-1021) and TN-68 (NRC Docket 72-1027) casks are evaluated here. The TN-32 cask accommodates 32 PWR fuel assemblies. The TN-68 cask accommodates up to 68 BWR fuel assemblies and is also licensed for transportation. Damaged fuel that can be handled by normal means may be stored in eight peripheral compartments of the TN-68 cask that are fitted with damaged-fuel end caps designed to retain gross fragments of fuel.

4.4.2 Bolted metal cask

The TN-32 and TN-68 cask body is a right circular cylinder composed of the following components: (i) confinement vessel with bolted lid closure, (ii) basket for fuel assemblies, (iii) gamma and neutron shield, (iv) pressure/leak-tightness monitoring system, (v) weather cover, and (vi) and trunnions. Figure 4-17 shows the components of the TN-32 cask, and Figure 4-18 shows the confinement-boundary components of the TN-68 cask. The details of the components of the TN-32 cask are provided below as an example of both TN metal casks.

Confinement boundary, closure lid, and pressure-monitoring system

The TN-32 cask confinement boundary consists of a welded cylindrical low-alloy steel inner shell with an integrally welded low-alloy steel bottom closure. A flange forging is welded to the top of the inner shell to accommodate a bolted low-alloy steel lid closure. The inner shell has a sprayed metallic aluminum coating for corrosion protection. The confinement vessel is surrounded by a carbon steel gamma shield wall and bottom. The cask is sealed with a carbon steel closure lid, which is secured to the top flange of the containment vessel by 48 bolts.

The closure lid uses a double-barrier seal system with two metallic O-rings (Helicoflex seals) forming the seal. The annular space between the metallic O-rings is connected to a pressure monitoring system placed between the lid and the protective cover, also called the weather cover, shown in Figure 4-19. Pressure in the tank of the pressure-monitoring system is maintained above the pressure in the cask cavity to prevent either flow of fission gases out of or air into the cask cavity, which, under normal storage conditions, is pressurized above atmospheric pressure with helium. The transducers/switches monitor the pressure in the annular space between the metallic O-rings to provide an indication of seal failure before any release is possible. Two identical transducers/switches are provided to ensure a functional system through redundancy.

The TN-32 cask body has four carbon steel trunnions that are welded to the gamma shield. Two of these are located near the top of the cylindrical steel forging, spaced 180 degrees apart, and are used for lifting the cask. The remaining two trunnions are 180 degrees apart and located near the bottom of the cask. The lower trunnions are used to rotate the unloaded cask between vertical and horizontal positions. The lifting trunnions are hollow to permit installation of neutron-shielding material and eliminate a path for neutron streaming. The TN-68 design differs from the TN-32 design in that its two top trunnions are bolted to the gamma shield.

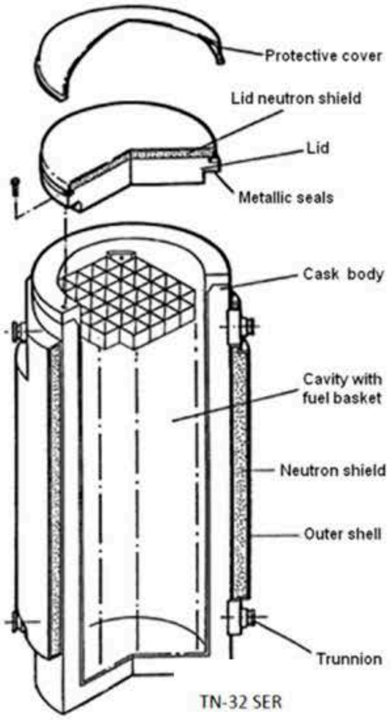


Figure 4-17 Components of the TN-32 storage cask (NRC, 1996)

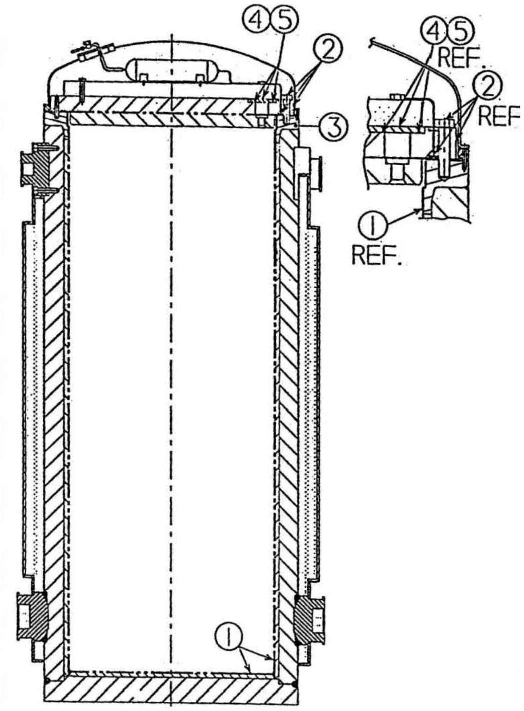


Figure 4-18 TN-68 cask confinement boundary components (Transnuclear Inc., 2005)

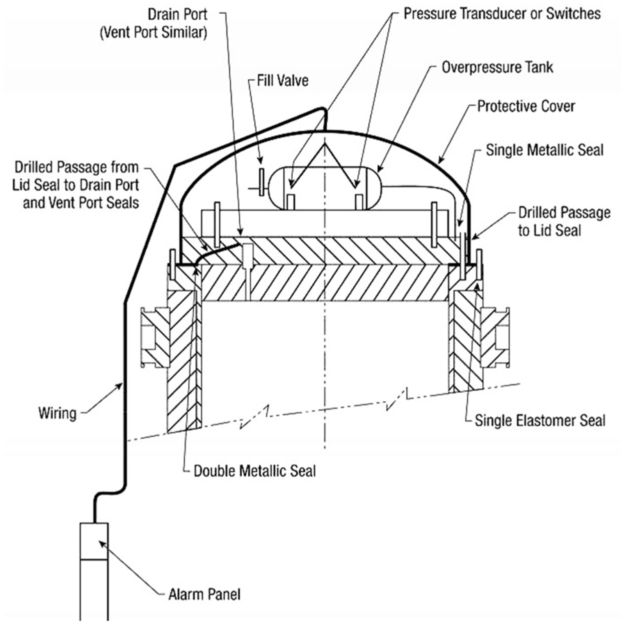


Figure 4-19 TN-32 cask seal pressure-monitoring system (NRC, 1996)

The TN-32 cask lid has three confinement access ports—a drain port, a vent port, and an overpressure system port. The drain and vent ports are covered by a bolted stainless steel closure plate having a double-barrier seal system with two metallic O-rings forming the seal, similar to the one used for the lid closure. The overpressure port is also covered by a bolted stainless steel closure plate but has a single metallic O-ring forming the seal. The closure lid has drilled interseal passageways connecting the annular space between the seals at each port to the annular space between the closure-lid seals, as shown in Figure 4-19. The cavity drain line penetrates the closure lid and terminates in the bottom of the cask cavity. This line is used to drain water from the cask cavity after underwater fuel loading. It is also used during the drying and helium backfilling of the cask cavity.

The all-metal Helicoflex seal used in the TN metal casks has a central helical energizing spring with inner and outer liners. Sealing is accomplished by plastic flow of the outer liner against the mating sealing surfaces. The helical spring aids in keeping a sufficient load against the outer liner to follow temperature fluctuations and small deformations.

The TN-32 confinement vessel has a cylindrical cavity that holds a fuel basket with 32 compartments to locate and support the PWR fuel assemblies. The basket assembly also transfers heat from the fuel assembly to the cask body wall and provides neutron absorption to satisfy nuclear criticality requirements, especially during loading and unloading operations that occur underwater. During storage, with the cavity dry, filled with inert gas, and sealed from the environment, criticality control measures within the cask are not necessary because of the low reactivity of the fuel in the dry cask and the assurance that no water can enter the cask during storage.

Fuel basket assemblies and shielding

The fuel cavities in the basket are formed by a sandwich of aluminum plates, Boral® plates, and stainless steel boxes. The stainless steel fuel-compartment box sections are attached by a series of stainless steel plugs that pass through the aluminum plates and the poison plates and are fusion-welded to both adjacent stainless steel box sections. The aluminum provides the heat-conduction paths from the fuel assemblies to the cask cavity wall. The poison material provides the necessary criticality control. The basket is held in place by aluminum rails that run the axial length of the cask body, as shown in Figure 4-20.

Surrounding the outside of the confinement vessel wall is a steel gamma shield, as shown in Figure 4-21. The bolted closure lid provides the gamma shielding at the upper end of the cask body. Neutron emissions from the stored fuel are attenuated by a neutron shield, consisting of a borated polyester resin compound, enclosed in long aluminum boxes that surround the gamma shield. These aluminum containers are held in place by a steel shell. Neutron emissions from the top of the cask are attenuated by a polypropylene disc, encased in a steel shell and placed on the top of the closure lid. There is no neutron shielding provided on the bottom of the cask.

The inside surfaces of the inner shell and bottom have a sprayed metallic coating of aluminum for corrosion protection. The external surfaces of the cask are metal-sprayed with aluminum and/or painted for ease of decontamination and corrosion protection. The neutron shield, pressure-monitoring system, and shield cap are placed on top of the cask after fuel is loaded into the cask. A stainless steel overlay is applied to the O-ring seating surfaces on the body for corrosion protection. A protective cover is bolted to the top of the cask body to provide weather protection for the lid penetrations and other components.

Table 4-11 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the TN-32 and TN-68 casks. The AMPs that provide an acceptable approach to managing the aging effects are also identified in the table.

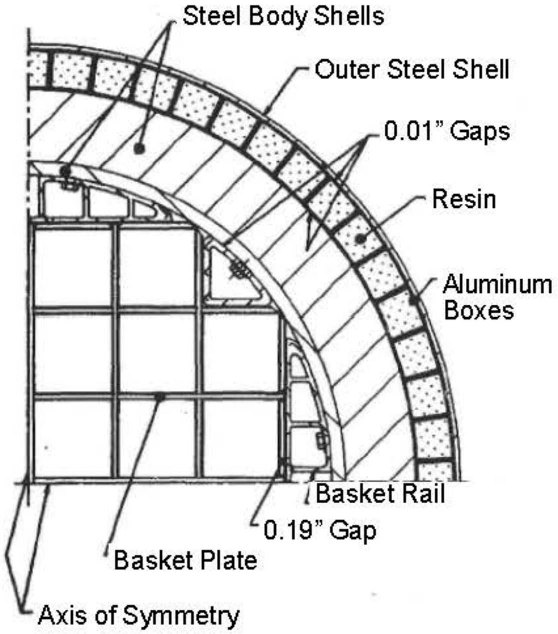


Figure 4-20 Radial cross section of TN-32 cask showing basket, basket rails, and gamma and neutron shields (NRC, 1996)

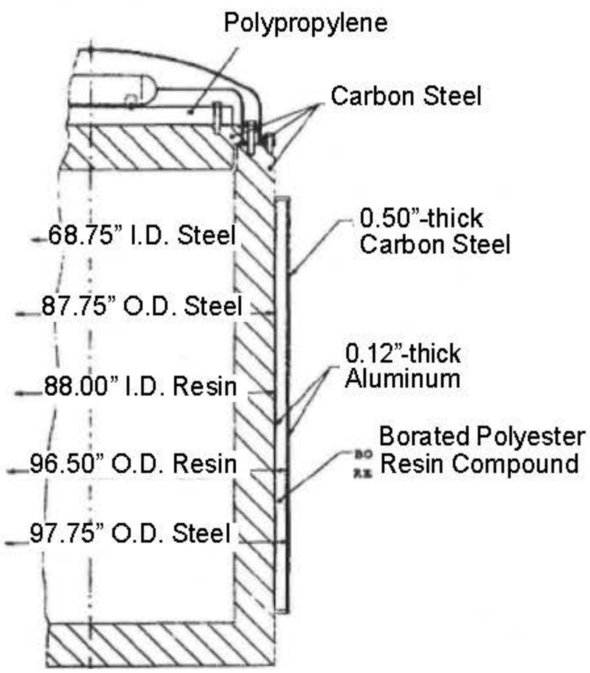


Figure 4-21 TN-32 cask shielding configuration (NRC, 1996)

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Outer shell	SH, SR, TH*	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Radial neutron shield	SH, TH	Borated polyester resin	Embedded (aluminum)	Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Radial neutron shield box	TH	Aluminum	Embedded (borated polyester resin)	Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Gamma shield	SH, SR, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Gamma shield	SH, SR, TH	Steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Cask body bottom	SH, SR, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Upper and lower trunnions	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Wear	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.11
Upper trunnion	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper trunnion	SR	Stainless steel	Air—outdoor	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.2.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.2.11
Trunnion bolts	SR	Steel	Air—outdoor	Stress relaxation	Loss of preload	No	3.2.1.10
				Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Trunnion cover screw	SH, SR	Stainless steel	Air—outdoor	Stress relaxation	Loss of preload	No	3.2.2.10
				Stress corrosion cracking	Cracking	No	3.2.2.5

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Trunnion cover screw	SH, SR	Stainless steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Top neutron shield	SH, TH	Polypropylene	Embedded (steel)	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Radiation embrittlement	Cracking	No	3.3.1.3
Top neutron shield bolt, vent & drain port cover bolts	SR	Stainless steel	Sheltered	Stress relaxation	Loss of preload	No	3.2.2.10
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Sheltered	Stress relaxation	Loss of preload	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.10
				Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.1

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top neutron shield bolt, vent & drain port cover bolts	SR	Steel	Sheltered	Galvanic corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Top neutron shield flat washer	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Lid	CO, SH, SR, TH	Steel	Sheltered	General corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.1
				Galvanic corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.2

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid	CO, SH, SR, TH	Steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
			Helium	General corrosion	Loss of material	No	3.2.1.1
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid assembly shim	SH, SR, TH	Steel	Embedded (steel)	Radiation embrittlement	Cracking	No	3.2.1.9
Flange	CO, SH, SR, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.1

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Flange	CO, SH, SR, TH	Steel	Sheltered	Galvanic corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
			Helium	General corrosion	Loss of material	No	3.2.1.1
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid bolts	CO, SH, SR, TH	Steel	Sheltered	Stress relaxation	Loss of preload	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.10
				Stress corrosion cracking	Cracking	No	3.2.1.5
				General corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.1
				Galvanic corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.1.2

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid bolts	CO, SH, SR, TH	Steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid threaded insert	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Lid seal, vent & drain port cover seal	CO, SH, SR, TH	Aluminum	Sheltered	General corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.3.1
				Galvanic corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.3.3
				Pitting and crevice corrosion	Loss of material	Bolted Cask Seal Leakage Monitoring AMP	3.2.3.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.3.4
				Radiation embrittlement	Cracking	No	3.2.3.8
			Helium	General corrosion	Loss of material	No	3.2.3.1

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid seal, vent & drain port cover seal	CO, SH, SR, TH	Aluminum	Helium	Thermal aging	Loss of strength	Bolted Cask Seal Leakage Monitoring AMP	3.2.3.7
				Creep	Change in dimensions	Bolted Cask Seal Leakage Monitoring AMP	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Drain port cover, vent port cover	CO, SH, SR, TH	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Lid shield plate	SH, SR, TH	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inner confinement shell, bottom confinement plate	CO, SH, SR, TH	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.1.9
Basket rails	SR, TH	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Thermal aging	Loss of strength	TLAA/AMP or a supporting analysis is required	3.2.3.7
				Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Basket rail shim	TH	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Basket shim	SR, TH	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Aluminum plate	TH	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Galvanic corrosion	Loss of material	No	3.2.3.3

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Aluminum plate	TH	Aluminum	Helium	Creep	Change in dimensions	No	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Poison plate	CR, TH	Borated aluminum	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Cracking	No	3.4.2.7
				Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
		Boron carbide/ aluminum metal-matrix composite	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Cracking	No	3.4.2.7
				Boron depletion	Loss of criticality control	No; a TLAA may be required.	3.4.2.4
		Boral®	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Wet corrosion and blistering	Change in dimensions	No	3.4.2.3
				Creep	Change in dimensions	No	3.4.2.5

Table 4-11 TN bolted metal casks

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Poison plate	CR, TH	Boral®	Helium	Radiation embrittlement	Cracking	No	3.4.2.7
				Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
Fuel compartment, structural plates, basket hold down	CR, SR, TH	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Basket shear key	SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9

4.5 NAC International Systems

4.5.1 System description

NAC International Inc. (NAC) has three dry storage systems (DSSs) approved for use under a general license: the Universal Storage System (NAC-UMS), the Multi-Purpose Canister (NAC-MPC) system, and the Modular Advanced Generation Nuclear All-Purpose Storage (MAGNASTOR) system. These systems are canister-plus-overpack designs that use a vertical concrete storage cask to house a stainless steel storage canister with a welded closure. The sections below describe the details of the three storage systems.

4.5.2 NAC-UMS

The principal components of NAC-UMS are the transportable storage canister (TSC), vertical concrete cask (VCC), and transfer cask (TC), as shown in Figure 4-22 (NAC International, 2004). There are five TSC configurations of different lengths for storage of different classes of PWR and BWR fuel assemblies. The TSC assembly consists of a right circular cylindrical shell with a welded bottom plate, fuel basket, shield lid, two penetration port covers, and a structural lid. The cylindrical shell, bottom plate, and lids constitute the confinement boundary. Figure 4-23 shows the various components of the NAC-UMS TSC for PWR fuel. All TSC components are made of stainless steel, with the exception of neutron poison plates, heat transfer disks, and support disks (BWR TSC fuel baskets only). The fuel basket is designed to accommodate up to 24 PWR or 56 BWR fuel assemblies. The fuel tubes are laterally supported by a series of stainless steel support disks in the PWR basket or carbon steel support disks in the BWR basket, which are retained by spacers on radially located tie rods. The carbon steel support disks are coated with electroless nickel. The square fuel tubes in the PWR basket include stainless-steel encased Boral® sheets on all four sides for criticality control. The square fuel tubes in the BWR basket may include stainless-steel encased Boral® sheets on up to two sides for criticality control. Aluminum heat transfer disks are spaced midway between the support disks and are the primary path for conducting heat from the fuel assemblies to the TSC wall.

The VCC is the storage overpack for the TSC and provides structural support, shielding, protection from environmental conditions, and natural convection cooling of the TSC during storage. Five concrete casks of different lengths are designed to accommodate different TSC configurations. The VCC side walls consist of reinforced concrete and a carbon steel inner liner. The VCC has an annular air passage to allow the natural circulation of air around the canister to remove the decay heat from the spent fuel stored in the TSC. The steel-lined air inlet and outlet vents take nonplanar paths to the cask cavity to minimize radiation streaming. The base plate assembly contains the air inlets and the pedestal that supports the TSC inside the VCC. The top of the VCC is closed by a shield plug consisting of a carbon steel plate for gamma shielding and solid neutron shielding of Bisco NS-3 or NS-4-FR, and a carbon steel lid. The carbon steel lid is installed above the shield plug and is bolted in place. The VCC is lifted from the bottom using an air-pad system. In an alternative design, a set of four carbon steel lifting lugs at the top of the VCC allows for lifting the cask with a loaded TSC from the top end.

The transfer cask is used for the vertical transfer of the TSC between workstations and the VCC. Five TCs of different lengths are designed to handle the five TSC configurations. The TC incorporates a multiwall (steel/lead/neutron shield/steel) design and a top retaining ring that is bolted in place to prevent a loaded canister from being inadvertently removed through the top of the TC. All transfer cask structural components are fabricated with high-strength, low-alloy steel, with the exception of stainless steel retaining-ring bolts and shield door lock bolts. The TC contains retractable bottom shield doors for transfer of the TSC from the transfer cask into the VCC, as shown in Figure 4-24. Shield door rails are welded to the bottom plate of the TC to facilitate TSC transfer. The TC has two trunnions near the top of the cask. The trunnions are welded to the inner and outer shells for vertical cask-handling operations. All of the exposed surfaces of the TC, other than the load-bearing surfaces of the trunnions and the bottom door rails, are coated with an epoxy enamel coating to protect the carbon steel and to provide a smooth surface to facilitate decontamination.

Table 4-12 through Table 4-14 provide a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the NAC-UMS. The tables also identify AMPs that provide an acceptable approach to managing the aging effects.

4.5.3 NAC-MPC

The NAC-MPC system is similar to the NAC-UMS but is designed for fuel from specific, older power plants. Like the UMS, the principal components of the NAC-MPC include a TSC, VCC, and a TC (NAC International, 2000).

The TSC contains a fuel basket that is designed to accommodate up to 36 PWR spent fuel assemblies and reconfigured fuel assemblies with up to 4 damaged fuel cans from the Yankee Rowe Nuclear Power Station, 24 or 26 PWR spent fuel assemblies and reconfigured fuel assemblies with up to 4 damaged fuel cans from the Connecticut Yankee Nuclear Power Plant, or 68 BWR spent fuel assemblies and reconfigured fuel assemblies with up to 32 damaged fuel cans from the LaCrosse Nuclear Generating Station.

The canister assembly for the Yankee Rowe and Connecticut Yankee configurations consists of a right circular cylindrical shell with a welded bottom plate, a fuel basket, a shield lid, two penetration port covers, and a structural lid. The cylindrical shell, bottom plate, and lids constitute the confinement boundary. The canister assembly for the La Crosse configuration consists of a right circular cylindrical shell with a welded bottom plate, a fuel basket, a closure lid, a closure ring, and two sets of redundant penetration port covers. The cylindrical shell, bottom plate, closure lid, and inner port covers constitute the confinement boundary.

All TSC components are made of stainless steel, with the exception of neutron poison plates, aluminum heat-transfer disks, and an aluminum spacer plate attached to the underside of the closure lid (La Crosse BWR-MPC only). The fuel tubes are laterally supported by a series of support disks that are retained by spacers on radially located tie rods. Aluminum heat-transfer disks are spaced midway between the support disks and are the primary path for conducting heat from the fuel assemblies in the TSC wall. The fuel assemblies are contained in square stainless steel fuel tubes. The fuel tubes are covered with stainless steel-encased Boral® sheets on all four sides for criticality control. An alternative fuel basket design has enlarged fuel tubes in the four corner locations. In this alternative configuration, the Boral® sheet and stainless steel cover are removed from each side of the fuel tube in the four corner locations.

The VCC serves as the storage overpack for the TSC and provides structural support, shielding, protection from environmental conditions, and natural convection cooling of the TSC during storage. The VCC is fabricated from reinforced concrete with a carbon steel liner and base. The VCC has an annular air passage to allow the natural circulation of air around the TSC. The air inlet and outlet vents are steel-lined penetrations that take nonplanar paths to the cask cavity to minimize radiation streaming. The base-plate assembly contains the air inlets and the pedestal that supports the TSC inside the VCC. The top of the VCCs for the Yankee Rowe and Connecticut Yankee configurations is closed by a shield plug and a carbon steel lid bolted in place. The shield plug incorporates a carbon steel plate for gamma shielding and Bisco NS-3 or NS-4-FR for neutron shielding. For the La Crosse configuration, the top of the VCC is closed by a carbon steel and concrete lid bolted in place. The steel-enclosed concrete extends into the cask cavity from the bottom surface of the carbon steel lid.

The TC is similar in design and construction to that of the UMS described in Section 4.5.2. It is a multiwall (steel/lead/neutron shield/steel) design with retractable bottom shield doors to allow the TSC to be lowered into the VCC.

Table 4-15 through Table 4-17 provide a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the NAC-MPC system. The tables also identify AMPs that provide an acceptable approach to managing the effects of aging.

4.5.4 MAGNASTOR

NAC developed the MAGNASTOR system to improve upon its previous designs in terms of storage capacity, thermal performance, and operations. The principal components of the MAGNASTOR system include a TSC with a welded closure, a concrete cask, and a TC (NAC International, 2015). Figure 4-25 presents schematics of the MAGNASTOR system.

The TSC consists of a right circular cylindrical shell with a welded bottom plate, a fuel basket, a closure lid, a closure ring, and two sets of redundant penetration port covers. There are two TSC lengths to accommodate fuel of different lengths. The cylindrical shell plus the bottom plate, closure lid, and welded inner port covers are constructed of stainless steel and constitute the confinement boundary. The closure ring and the outer redundant port covers are also stainless steel and provide the required redundant closure for a welded canister system. There is an alternative closure lid design with a two-piece composite lid assembly that consists of a stainless steel closure lid and a carbon steel shield plate. The shield plate is coated with electroless nickel and bolted to the closure lid. The fuel basket, fabricated from carbon steel and coated with electroless nickel, is designed to accommodate up to 87 BWR fuel assemblies or 37 PWR fuel assemblies, including up to four damaged fuel can locations. The fuel basket design is an arrangement of square fuel tubes held in a right circular cylinder configuration using support weldments that are bolted to the outer fuel tubes. The fuel assembly cells in the fuel baskets include neutron absorber panels on up to four sides for criticality control. The materials of construction for the neutron absorber panels include Boral®, borated aluminum, and borated metal matrix composite. Each neutron absorber panel is covered by a stainless steel sheet to protect the material during fuel loading and unloading and to maintain it in position. The neutron absorber and stainless steel cover are secured to the fuel tube using weld posts located across the width and along the length of the fuel tube.

The concrete cask is the storage overpack for the TSC and provides structural support, shielding, protection from environmental conditions, and natural convection cooling of the TSC during storage. The concrete cask is a reinforced concrete structure with a carbon steel inner liner and base, shown in Figure 4-26 (NAC International, 2014). There are four concrete cask configurations of different lengths and design variations. The concrete cask provides an annular air passage to allow the natural circulation of air around the TSC to remove the decay heat from the stored spent fuel. The lower air inlets and upper air outlets are steel-lined penetrations in the concrete cask body. The base plate assembly contains the air inlets and the pedestal that supports the TSC. Carbon steel channels that are attached to the inner liner assist in centering the TSC in the overpack. The top of the concrete cask is closed by a carbon steel and concrete lid bolted in place. The concrete cask is lifted by means of carbon steel lift anchor and lug assemblies embedded in the top of the concrete cask body. Alternatively, the concrete cask can be lifted and moved by means of air pads inserted into the four lower inlets.

The transfer cask provides shielding during TSC movements between workstations and the concrete cask. The TC is provided in two different configurations (referred to as MTC1 and MTC2) that differ primarily in the structural materials and overall length. The materials of construction for the TC structural components are carbon steel for the MTC1 configuration and stainless steel for the MTC2 configuration. The TC is a multiwall (steel/lead/NS-4-FR/steel) design. It incorporates stainless steel retaining blocks or a bolted retaining ring to prevent a loaded TSC from being inadvertently removed through the top of the TC. The TC contains retractable bottom shield doors that are used during TSC loading and unloading operations. Shield door rails are welded to the bottom ring of the TC to facilitate TSC transfer. The TC has two trunnions near the top of the cask that are welded to the top ring for vertical cask-handling operations. The exposed carbon steel surfaces of the MTC1 transfer cask, except for the wear surfaces of the shield doors and rails, are coated with an epoxy enamel coating to protect the components from corrosion and adverse interactions with the operating environments.

Table 4-18 through Table 4-20 provide a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the MAGNASTOR system. The tables also identify AMPs that provide an acceptable approach to managing the aging effects.

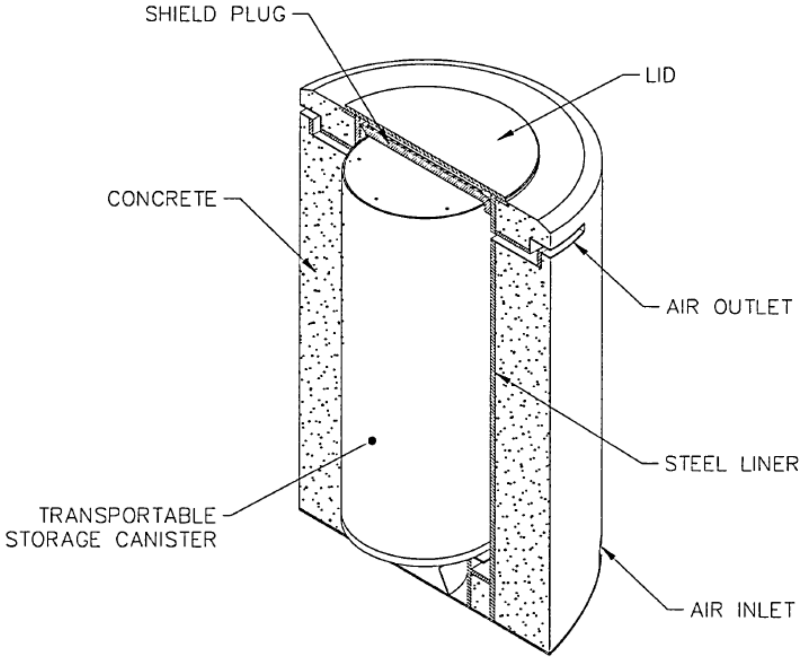


Figure 4-22 NAC-UMS (NAC International, 2004)

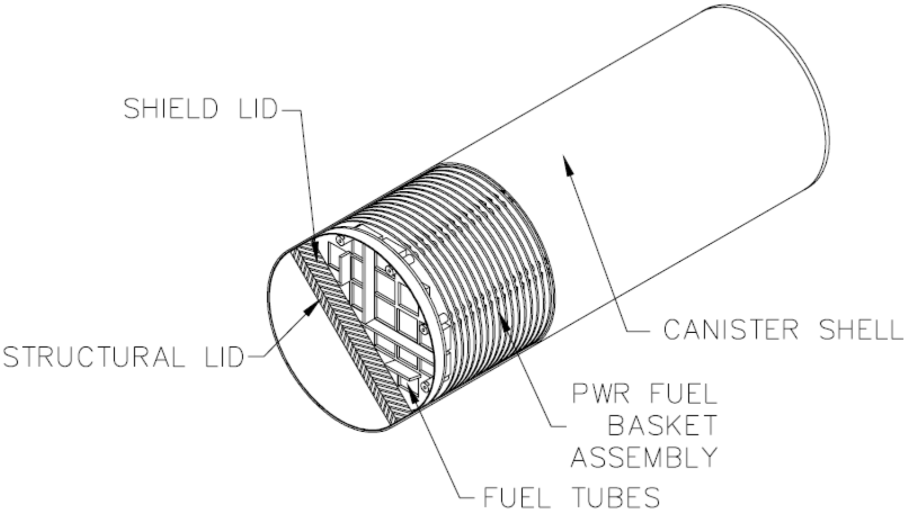


Figure 4-23 NAC-UMS transportable storage canister for PWR fuel (NAC International, 2004)

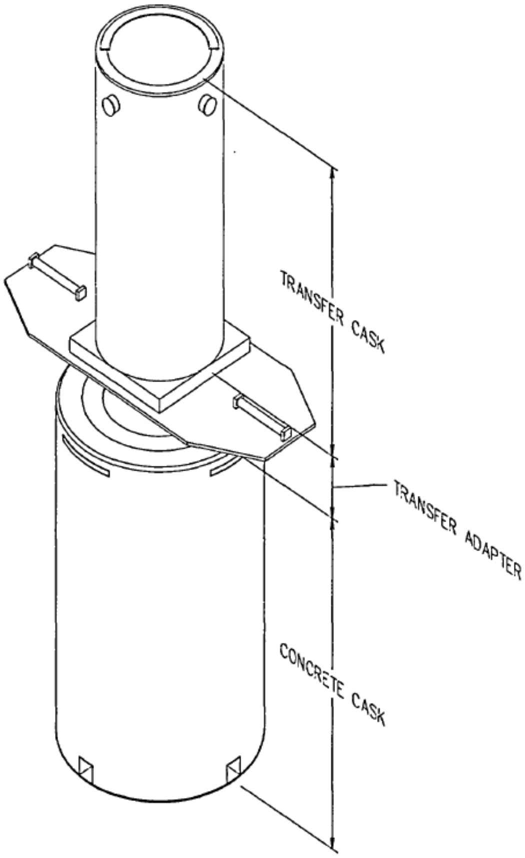


Figure 4-24 NAC-UMS VCC and transfer cask arrangement (NAC International, 2004)

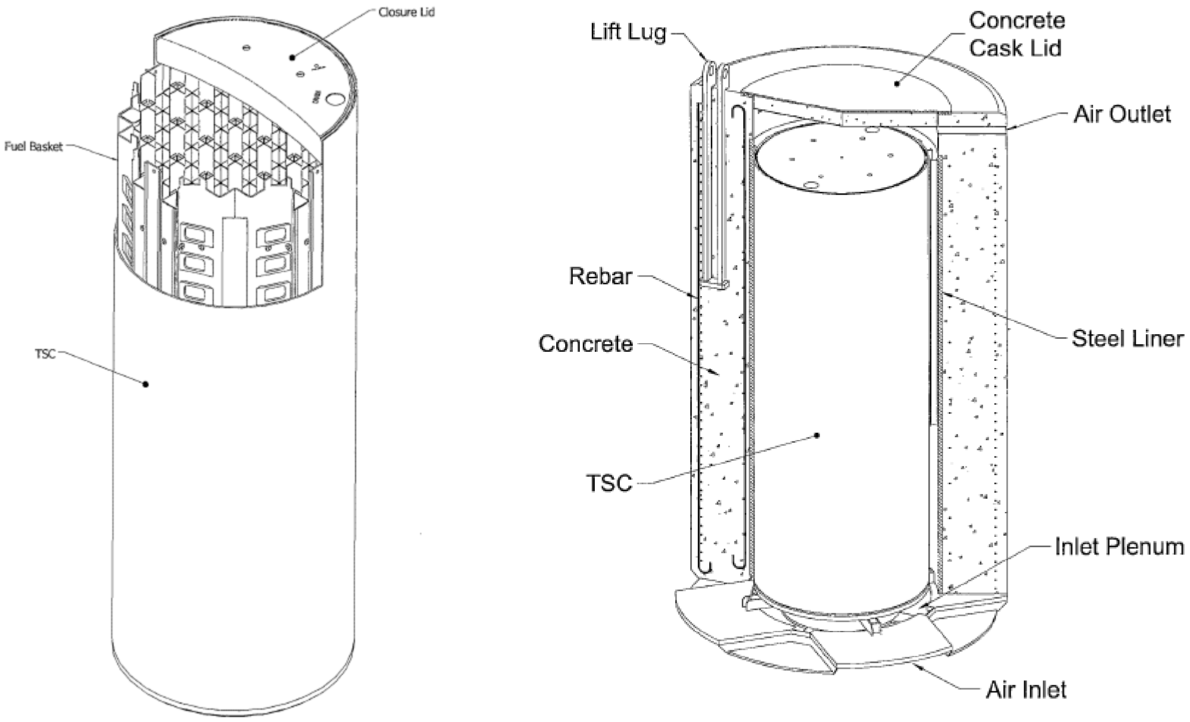


Figure 4-25 NAC MAGNASTOR TSC and concrete cask (NAC International, 2015)

Figure 4-26 NAC MAGNASTOR concrete cask (NAC International, 2014)

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shell	CO, SR*	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Bottom	CO, SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom	CO, SR	Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Strucural lid	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Spacer ring	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Shield lid, support ring	SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Port cover	CO	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Port cover	CO	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Fuel tube, cladding, flange	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Neutron absorber	CR	Boral	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Wet corrosion and blistering	Change in dimensions	No	3.4.2.3
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Cracking	No	3.4.2.7
				Boron depletion	Loss of criticality control	No; a TLAA may be required.	3.4.2.4

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket bottom weldment	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket top weldment	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket tie rod, spacer, washer	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket support disk	SR	Stainless steel (17-4 PH)	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
Fuel basket top nut	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket top nut	SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Fuel basket heat transfer disk	TH	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Maine Yankee fuel can tube body	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Maine Yankee fuel can bottom and side plates	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Maine Yankee fuel can bottom and side plates	CR, SR	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Maine Yankee fuel can lid plate, lid bottom	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Maine Yankee fuel can lift tee, support ring	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Maine Yankee fuel can lid collar, screen	CO	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6

Table 4-12 NAC-UMS transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Maine Yankee fuel can lid collar, screen	CO	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell	SH, SR*	Concrete	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell	SH, SR	Concrete	Air—outdoor	Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
		Reinforcing steel	Air—outdoor, groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inner shell	SH, SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Top flange, support ring	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Pedestal plate	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Pedestal plate	SR	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Pedestal cover	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Base plate assembly	SH, SR, TH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Base plate nelson studs	SR	Steel	Embedded (concrete)	General corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.1
				Pitting and crevice corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Outlet vent assembly	SH, SR, TH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Inlet and outlet vent hardware	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inlet and outlet vent hardware	SR	Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Inlet vent supplemental shielding assembly	SH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid	SR	Steel	Air—outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid hardware	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Shield plug assembly	SH, SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield plug assembly	SH, SR	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Neutron shield (Shield plug)	SH	NS-4-FR	Embedded (steel)	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
		NS-3	Embedded (steel)	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.3.1.2
				Radiation embrittlement	Cracking	No	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Lift anchor	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lift anchor	SR	Steel	Air—outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	General corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.1
				Pitting and crevice corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lift lug	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lift anchor hardware	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-13 NAC-UMS vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lift anchor hardware	SR	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10

Table 4-14 NAC-UMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Outer shell	SR*	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Galvanic corrosion	Loss of material	Transfer Casks AMP	3.2.1.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (NS-4-FR)	Radiation embrittlement	Cracking	No	3.2.1.9
Inner shell	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9
Gamma shield (Cask body)	SH	Lead	Embedded (steel, NS-4-FR)	None identified	None identified	No	3.2.6

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-14 NAC-UMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield (Cask body)	SH	NS-4-FR	Embedded (steel, lead)	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Top plate	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Bottom plate	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-14 NAC-UMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Retaining ring	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Galvanic corrosion	Loss of material	Transfer Casks AMP	3.2.1.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Retaining ring bolts	SR	Stainless steel (ferritic)	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Trunnion	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2

Table 4-14 NAC-UMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Trunnion	SR	Steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
Shield door plates	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.3
				Radiation embrittlement	Cracking	No	3.2.1.9
Shield door rails	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Galvanic corrosion	Loss of material	Transfer Casks AMP	3.2.1.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11

Table 4-14 NAC-UMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield door lock bolts	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Transfer adapter	SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Wear strip	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5

Table 4-14 NAC-UMS transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Wear strip	SR	Stainless steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shell	CO, SR*	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.2.2.9
Bottom	CO, SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom	CO, SR	Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Closure lid; structural lid	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Closure ring; spacer ring	SR	Stainless steel (welded)	Sheltered	Atmospheric stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Closure lid assembly bolt, washer	SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Closure lid assembly spacer	SR	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Galvanic corrosion	Loss of material	No	3.2.3.3
				Thermal aging	Loss of strength	TLAA/AMP or a supporting analysis is required	3.2.3.7
				Creep	Change in dimensions	TLAA/AMP or a supporting analysis is required	3.2.3.5

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Closure lid assembly spacer	SR	Aluminum	Helium	Radiation embrittlement	Cracking	No	3.2.3.8
Shield lid, support ring	SH, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Port cover	CO	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
			Sheltered	Atmospheric stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
			Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Port cover	CO	Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel tube, cladding, flange	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Neutron absorber	CR	Boral	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Wet corrosion and blistering	Change in dimensions	No	3.4.2.3
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Cracking	No	3.4.2.7

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron absorber	CR	Boral	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
Plate in lieu of neutron absorber	TH	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Galvanic corrosion	Loss of material	No	3.2.3.3
				Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Fuel basket bottom weldment	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket top weldment	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket top weldment	SR	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket tie rod, spacer, washer	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket support disk	SR	Stainless steel (17-4 PH)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket top nut	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket top nut	SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Fuel basket heat transfer disk	TH	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Damaged fuel can tube body	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can bottom and side plates, screen cover plate	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Damaged fuel can bottom and side plates, screen cover plate	CR, SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can lid plate, lid bottom	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can lift tee, support ring	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can screen	CO	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Damaged fuel can screen	CO	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Removable fuel rod retainer assembly (Yankee-MPC)	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Reconfigured fuel assembly shell casing, top ring (Yankee-MPC)	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Reconfigured fuel assembly top end fitting assembly (Yankee-MPC)	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reconfigured fuel assembly top end fitting assembly (Yankee-MPC)	CR, SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Reconfigured fuel assembly bottom end fitting assembly (Yankee-MPC)	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Reconfigured fuel assembly top nozzle bolt (Yankee-MPC)	CR, SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Reconfigured fuel assembly fuel basket corner angle, tie plate (Yankee-MPC)	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reconfigured fuel assembly fuel basket corner angle, tie plate (Yankee-MPC)	CR, SR	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Reconfigured fuel assembly fuel tube, top and bottom caps (Yankee-MPC)	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Reconfigured fuel assembly fuel tube, corner angle, support grid (CY-MPC)	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-15 NAC-MPC transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reconfigured fuel assembly screens (CY-MPC)	CO	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Reconfigured fuel assembly top and bottom housing, retaining plate and ring, guide plate, rod retaining plate, screen ring and housing (CY-MPC)	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell	SH, SR*	Concrete	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperature	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell	SH, SR	Concrete	Air—outdoor	Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
		Reinforcing steel	Air—outdoor, groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, caling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inner shell	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Top flange, support ring	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Pedestal plate	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Pedestal cover	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Base plate assembly	SH, SR, TH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Base plate nelson studs	SR	Steel	Embedded (concrete)	General corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.1
				Pitting and crevice corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Outlet vent assembly	SH, SR, TH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Outlet vent assembly	SH, SR, TH	Steel	Sheltered	Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Inlet and outlet vent hardware	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Inlet vent supplemental shielding assembly	SH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inlet vent supplemental shielding assembly	SH	Steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid assembly	SH, SR, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid assembly	SH, SR, TH	Steel	Sheltered	Radiation embrittlement	Cracking	No	3.2.1.9
		Concrete	Embedded (steel)	Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Cracking	No	3.5.1.13
					Loss of strength	No	3.5.1.13
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Reaction with aggregates	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.3
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.3
Lid center support, nelson studs	SR	Steel	Embedded (concrete)	General corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.1
				Pitting and crevice corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid hardware	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Shield plug assembly	SH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Neutron shield (Shield plug)	SH	NS-4-FR	Embedded (steel)	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2

Table 4-16 NAC-MPC vertical concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield (Shield plug)	SH	NS-4-FR	Embedded (steel)	Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
		NS-3	Embedded (steel)	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.3.1.2
				Radiation embrittlement	Cracking	No	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1

Table 4-17 NAC-MPC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Outer shell	SR*	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Galvanic corrosion	Loss of material	Transfer Casks AMP	3.2.1.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (NS-4-FR)	Radiation embrittlement	Cracking	No	3.2.1.9
Inner shell	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9
Gamma shield (Cask body)	SH	Lead	Embedded (steel, NS-4-FR)	None identified	None identified	No	3.2.6

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-17 NAC-MPC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield (Cask body)	SH	NS-4-FR	Embedded (steel, lead)	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Top plate	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Bottom plate	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-17 NAC-MPC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Retaining ring	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Galvanic corrosion	Loss of material	Transfer Casks AMP	3.2.1.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Retaining ring bolts	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Trunnion	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-17 NAC-MPC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Trunnion	SR	Steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
Shield door plates	SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Shield door rails	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Galvanic corrosion	Loss of material	Transfer Casks AMP	3.2.1.3
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
Shield door lock bolts	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2

Table 4-17 NAC-MPC transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield door lock bolts	SR	Stainless steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shell	CO, SR*	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Bottom	CO, SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
				Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom	CO, SR	Stainless steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Closure lid	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Closure ring	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Closure lid assembly bolt, washer	SR	Stainless steel	Helium	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Closure lid shield plate	SH, SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Galvanic corrosion	Loss of material	No	3.2.1.3
				Pitting and crevice corrosion	Loss of material	No	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Port cover	CO	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Port cover	CO	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Lifting lug, anti-rotation lug	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel tube	CR, SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
Neutron absorber	CR	Borated aluminum	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Creep	Change in dimensions	No	3.4.2.5

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron absorber	CR	Borated aluminum	Helium	Radiation embrittlement	Cracking	No	3.4.2.7
				Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
		Boral	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Wet corrosion and blistering	Change in dimensions	No	3.4.2.3
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Cracking	No	3.4.2.7
				Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
		Borated metal matrix composite	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Cracking	No	3.4.2.7

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron absorber	CR	Borated metal matrix composite	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
Plate in lieu of neutron absorber	TH	Aluminum	Helium	General corrosion	Loss of material	No	3.2.3.1
				Galvanic corrosion	Loss of material	No	3.2.3.3
				Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8
Neutron absorber retainer	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Weld post	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Weld post	SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket support plates & gussets, connector pin washer	SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
Neutron absorber retainer clip, fuel basket support tube, vent and drain tube restrictor plate, fuel basket pins, spacer	SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket corner support bar, support pin, fuel tube pin, connector pin	SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
Basket restraining block	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Basket support mounting bolt	SR	Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8

Table 4-18 MAGNASTOR transportable storage canister							
Structure, System, or Component	**Intended Safety Function**	**Material**	**Environment**	**Aging Mechanism**	**Aging Effect**	**Aging Management**	**Technical Basis (Section)**
Basket support mounting bolt	SR	Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Basket support washer, blocking strap	SR	Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Basket shim	SR	Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can tube body	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Damaged fuel can tube body	CR, SR	Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can bottom, side plates	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can lid plate, lid guide, lid bottom	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Damaged fuel can collar, lift tee, support ring, tid tab	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can screens	CO	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel spacer plate	SR	Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-18 MAGNASTOR transportable storage canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Damaged fuel closure lid shield plate	SH	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell	SH, SR*	Concrete	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell	SH, SR	Concrete	Air—outdoor	Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedements)	Reinforced Concrete Structures AMP	3.5.1.8
		Reinforcing steel	Air—outdoor, groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6
Inner shell	SR, SH, TH	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inner shell	SR, SH, TH	Steel	Sheltered	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Top flange	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Pedestal plate	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Pedestal cover	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Base plate assembly (including nelson studs)	SH, SR, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Base plate assembly (including nelson studs)	SH, SR, TH	Steel	Air—outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Channels	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lid assembly	SH, SR, TH	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid assembly	SH, SR, TH	Steel	Air—outdoor	Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
		Concrete	Embedded (steel)	Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Cracking	No	3.5.1.13
					Loss of strength	No	3.5.1.13
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Reaction with aggregates	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.3

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lid assembly	SH, SR, TH	Concrete	Embedded (steel)	Reaction with aggregates	Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.3
Lid hardware	SR	Stainless steel	Air—outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Lift anchor (standard configuration)	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lift anchor (standard and alternative configurations)	SR	Steel	Embedded (concrete)	General corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.1
				Pitting and crevice corrosion	Loss of material	TLAA/AMP or a supporting analysis is required	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lift anchor (standard and alternative configurations)	SR	Steel	Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Lift lug	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Lift lug bolt	SR	Nickel alloy	Sheltered	Stress corrosion cracking	Cracking	No	3.2.4.4
				Pitting and crevice corrosion	Loss of material	No	3.2.4.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.4.3
				Radiation embrittlement	Cracking	No	3.2.4.6
				Stress relaxation	Loss of preload	No	3.2.4.7
Lift lug washer, base plate dowel pin	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4

Table 4-19 MAGNASTOR concrete cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Lift lug washer, base plate dowel pin	SR	Stainless steel	Sheltered	Radiation embrittlement	Cracking	No	3.2.2.9
Cover plate	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Cover plate hardware	SR	Stainless steel	Air—outdoor	Stress-corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Outer shell	SR*	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (NS-4-FR)	Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (NS-4-FR)	Radiation embrittlement	Cracking	No	3.2.2.9
Inner shell	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Inner shell	SR	Steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (lead)	Radiation embrittlement	Cracking	No	3.2.2.9
Gamma shield (Cask body)	SH	Lead	Embedded (steel, NS-4-FR)	None identified	None identified	No	3.2.6
			Embedded (stainless steel, NS-4-FR)	None identified	None identified	No	3.2.6
Neutron shield (Cask body)	SH	NS-4-FR	Embedded (steel, lead)	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield (Cask body)	SH	NS-4-FR	Embedded (steel, lead)	Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
			Embedded (stainless steel, lead)	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.3.1.2
				Radiation embrittlement	Cracking	TLAA/AMP or a supporting analysis is required	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Top ring	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom ring	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
Trunnion	SR	Steel	Air—indooroutdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Trunnion	SR	Stainless steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.2.9
Trunnion bushing, rotating bushing	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
Shield door plates	SH	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield door rails	SH, SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
				Wear	Loss of material	Transfer Casks AMP	3.2.1.11
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
Shield door tab	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield door tab	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
Shield door lock pin	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
Retaining block and ring	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
Retaining pin	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Retaining pin	SR	Steel	Air—indoor/outdoor	Radiation embrittlement	Cracking	No	3.2.1.9
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
Retainer assembly spring plunger, guide bolt, handle bolt	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Retainer assembly handle	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-20 MAGNASTOR transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Retaining ring bolt and screw thread	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Wear strip (cask attachment)	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
Fill/drain assembly tube and bar	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress-corrosion cracking	Cracking	No	3.2.2.5
				Radiation embrittlement	Cracking	No	3.2.2.9

4.6 FuelSolutions^{TM} storage system

4.6.1 System description

The FuelSolutions^{TM} storage system uses a stainless steel storage canister stored within a vertical cylindrical concrete storage cask. The principal components of the storage system are the W21 and W74 canisters, the W150 concrete storage cask, and the W100 transfer cask. The W21 canister is designed to accommodate nearly all domestic commercial spent nuclear fuel with a capacity of up to 21 PWR fuel assemblies. The W74 canister is designed to accommodate the three assembly types used at the Big Rock Point Nuclear Plant, including mixed oxide, partial, and damaged fuel assemblies, with a capacity of up to 64 BWR fuel assemblies. The W150 concrete storage cask provides radiation shielding and contains internal air flowpaths that allow decay heat from the canister spent fuel contents to be removed by natural air circulation around the canister wall. The W100 TC is used to move the loaded canisters to and from the storage cask. The sections below summarize the components of the FuelSolutions^{TM} storage system.

4.6.2 W21 and W74 canisters

The W21 and W74 canisters, shown in Figure 4-27, each have several design configurations consisting of different materials of construction and dimensions. A typical W21 or W74 canister consists of a shell assembly, top and bottom inner closure plates, vent and drain port covers, internal basket assembly, top and bottom shield plugs, and top and bottom outer closure plates. All structural components of the canister are constructed of high-strength carbon or stainless steel. Any carbon steel used in the canister is coated with electroless nickel for corrosion protection. The canister shell, top and bottom inner closure plates, and vent and drain port covers form the confinement boundary and are fabricated from stainless steel.

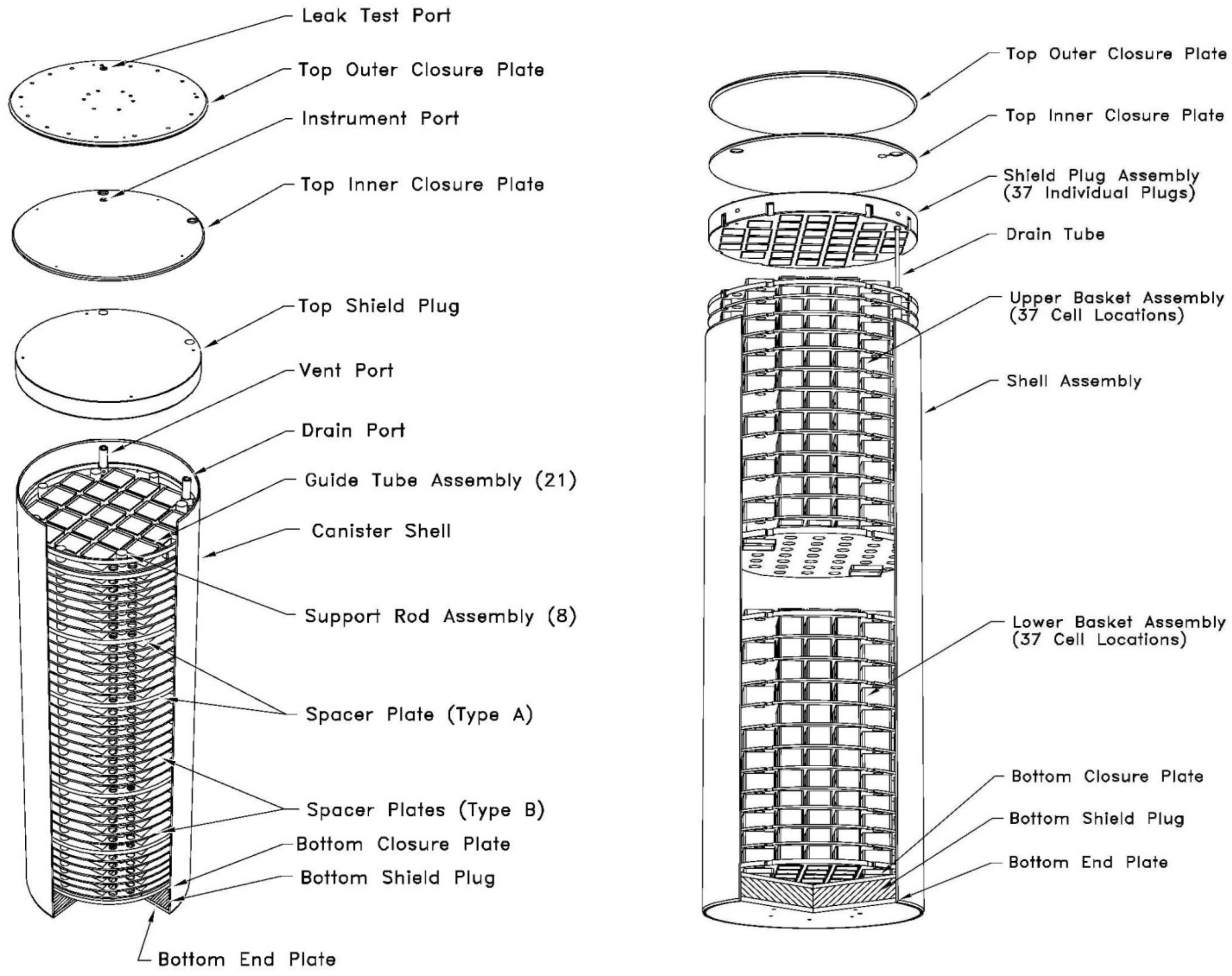
W21 basket assembly

The W21 PWR fuel basket assembly is a right circular cylinder configuration with 21 stainless steel guide tubes for PWR contents (FuelSolutions, 2007a). The guide tubes are laterally supported by a series of spacer plates, held in position by support rods that run through support rod sleeves placed between the spacer plates. The square guide tubes include Boral® neutron poison sheets on all four sides for criticality control. There are two classes of canister for the W21 canister based on different materials of construction: W21M and W21T. Each class of canister has four different types, which differ in dimension (exterior canister length and internal cavity length) and the material used for end plug shielding (steel, lead, or depleted uranium (W21M only)).

W74 basket assembly

The W74 BWR fuel basket assembly consists of two right circular cylindrical baskets, with a total of 56 guide tubes and a capacity of up to 64 assemblies (FuelSolutions, 2007b). The guide tubes are supported by a series of spacer plates held in position by support rods that run through support rod sleeves placed between the spacer plates. The square guide tubes include neutron poison sheets made of borated stainless steel, either on one side or on two opposite sides, in an arrangement within the basket that assures that there is a poison sheet between all of the assemblies. There are two classes of canister for the W74 canister based on different materials of construction (W74M and W74T). Unlike the W21 design, each W74 canister class has only one canister length and one cavity size, and carbon steel is used for end plug shielding material.

Table 4-21 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the W21 and W74 canisters. The table also identifies AMPs that provide an acceptable approach to managing the aging effects.



(a) (b)

Figure 4-27 Typical FuelSolutions™ (a) W21 and (b) W74 canisters (FuelSoutions, 2007a,b)

4.6.3 W150 storage cask

The W150 storage cask, shown in Figure 4-28, is the overpack for storing both the long and short versions of the W21 and W74 canisters by varying the length of the middle concrete segment (FuelSolutions, 2007c). The overpack consists of a standard reinforced concrete structure with three precast segments (top, middle, and bottom) and a top cover made of steel and concrete. Stainless steel tie rods are used to tie the concrete segments together. A shear key between each two concrete segments provides positive lateral engagement and alignment and serves to minimize radiation streaming. Grout is installed between the keyed joints of the concrete segments to provide a weather barrier. The exterior surfaces of the concrete are exposed to the outdoor environment.

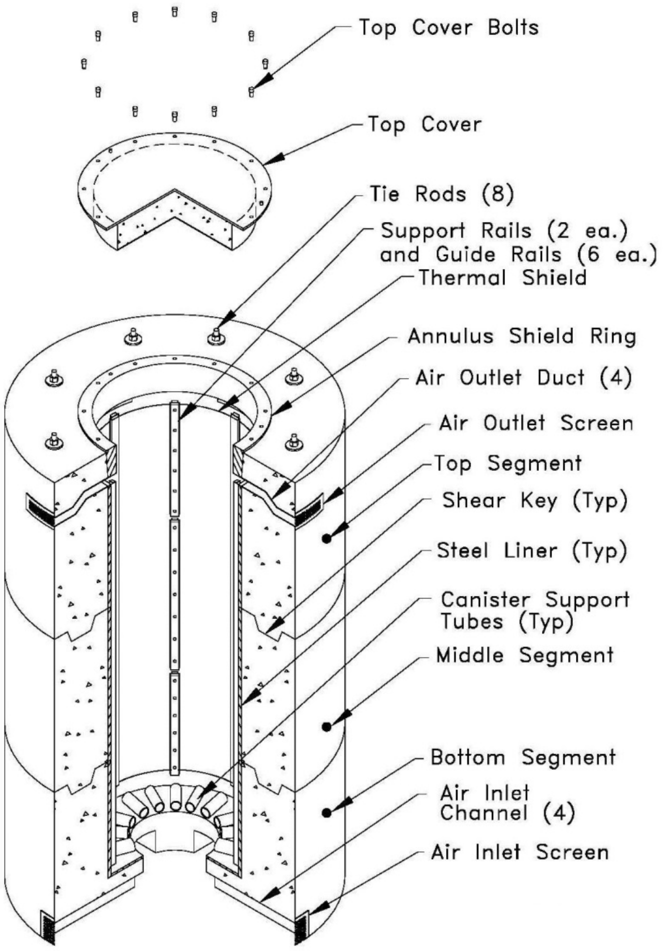


Figure 4-28 FuelSolutions^{TM} W150 storage cask (FuelSolutions, 2007c)

The top cover of the overpack is bolted to the overpack top end segment shielding ring and is sealed with weather sealant. Inside the cavity of the overpack are a steel liner, an aluminum thermal shield, steel support and guide rails, and stainless steel canister support tubes. Guide rails are welded to the steel liner for centering the canister radially in the cavity. Canister support tubes are welded to the bottom plate of the steel liner plate to provide vertical support of the canister and to limit the g-load on the canister in a postulated accident. All steel components, such as the liner, top cover, and support and guide rails, are coated with temperature- and radiation-resistant coatings.

The overpack concrete bottom segment includes four inlet vents that converge into a single cylindrical inlet duct at the bottom center of the cask cavity. The center inlet duct also provides hydraulic ram access during horizontal canister transfer operations. The inlet and outlet vents have protective screens to prevent debris or wildlife from entering the ventilation ducts.

Table 4-22 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the W150 storage cask. The table also identifies AMPs that provide an acceptable approach to managing the aging effects.

4.6.4 W100 transfer cask

The W100 TC, shown in Figure 4-29, is a multiwall, stainless steel cylindrical vessel with covers on both ends (FuelSolutions, 2007c). The TC is composed of a structural shell and a stainless steel inner liner, with lead in the annular space to provide gamma shielding. The TC also includes an outer stainless steel jacket filled with demineralized water for neutron shielding. The penetrations in the neutron shield cavity consist of two quick-connect fittings that are used to drain and fill the neutron shield cavity and to prevent intrusion of contaminated spent fuel pool water. A pressure relief device is used to provide over-pressure protection for the neutron shield.

The structural shell and inner liner are welded to stainless steel flanges at the top and bottom ends. Both the top and bottom covers are made of stainless steel plates and an encased solid neutron shielding of RX-277 or BISCO NS-3. The top cover includes a secondary central cover for ram access during horizontal loading and unloading operations. The bottom cover has O-rings to prevent spent fuel pool water from entering the cask during loading operations. Nitronic 60 stainless steel guide rails are welded to the inner shell cavity to facilitate horizontal canister transfer.

The W100 TC has four stainless steel trunnions. Two upper lifting trunnions located near the top of the cask for vertical cask handling operations are welded to the structural shell and inner liner. The lower trunnions used for upending and downending the TC are welded to the structural shell. Heat removal from the TC is primarily by conduction through the cask wall. A high emissivity, low absorptivity coating is applied to the exterior of the liquid neutron shield jacket to facilitate radiative heat transfer to the environment.

Table 4-23 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the W100 TC. The table also identifies AMPs that provide an acceptable approach to managing the aging effects.

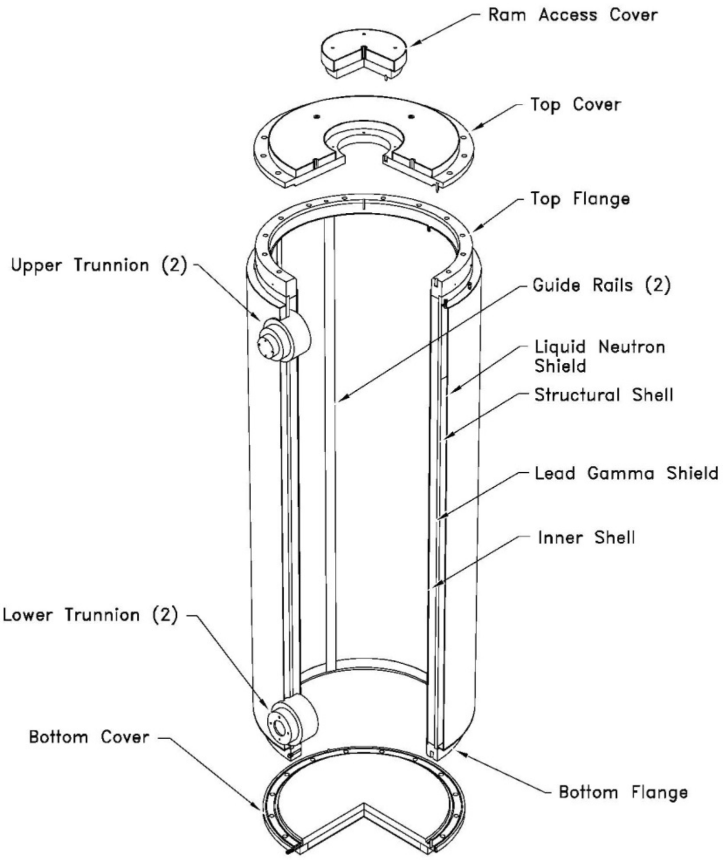


Figure 4-29 FuelSolutions^{TM} W100 transfer cask (FuelSolutions, 2007c)

Table 4-21 FuelSolutions^{TM} canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shell	CO, SR*	Stainless steel (welded)	Sheltered	Stress-corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Bottom closure plate	CO, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-21 FuelSolutions^{TM} canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom closure plate	CO, SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (steel, depleted uranium)	Radiation embrittlement	Cracking	No	3.2.2.9
Bottom end plate	SR	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress-corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
			Embedded (steel, depleted uranium)	Radiation embrittlement	Cracking	No	3.2.2.9
Top outer closure plate	CO, SR*	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5

Table 4-21 FuelSolutions™ canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top outer closure plate	CO, SR	Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Top inner closure plate	CO, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Alignment bar, adapter	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-21 FuelSolutions^{TM} canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shield plug	SH	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Galvanic corrosion	Loss of material	No	3.2.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (stainless steel)	Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (stainless steel, depleted uranium)	Radiation embrittlement	Cracking	No	3.2.1.9
		Lead	Embedded (stainless steel)	None identified	None identified	No	3.2.6
		Depleted uranium	Embedded (stainless steel)	None identified	None identified	No	3.2.7
			Embedded (stainless steel, steel)	None identified	None identified	No	3.2.7
Shield plug support assembly	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-21 FuelSolutions^{TM} canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Leak test port cover	CO	Stainless steel (welded)	Sheltered	Stress corrosion cracking	Cracking	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.5
		Stainless steel	Sheltered	Pitting and crevice corrosion	Loss of material (Precursor to stress corrosion cracking)	Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Instrument port cover, vent/drain port cover	CO	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Vent and drain port	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Creep	Change in dimensions	No	3.2.2.6

Table 4-21 FuelSolutions$^{\mathrm{TM}}$ canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Vent and drain port	SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Guide tube assembly	CR, SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Neutron absorber	CR	Boral	Helium	General corrosion	Loss of material	No	3.4.2.1
				Galvanic corrosion	Loss of material	No	3.4.2.2
				Thermal aging	Loss of strength	No	3.4.2.6
				Wet corrosion and blistering	Change in dimensions	No	3.4.2.3
				Creep	Change in dimensions	No	3.4.2.5
				Radiation embrittlement	Cracking	No	3.4.2.7
				Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.2.4
		Borated stainless steel	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.4.1.3
				Creep	Change in dimensions	No	3.4.1.2
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.1.4

Table 4-21 FuelSolutions^{TM} canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket support rod, support sleeve	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket support rod	SR	Stainless steel (17-4 PH)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	TLAA/AMP or a supporting analysis is required	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Fuel basket support sleeve	SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Galvanic corrosion	Loss of material	No	3.2.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-21 FuelSolutions™ canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket bolt	SR	Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Galvanic corrosion	Loss of material	No	3.2.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7
				Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	TLAA/AMP or a supporting analysis is required	3.2.1.10
Fuel basket spacer assembly	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
		Steel	Helium	General corrosion	Loss of material	No	3.2.1.1
				Galvanic corrosion	Loss of material	No	3.2.1.3
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.1.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.1.7

Table 4-21 FuelSolutions^{TM} canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel basket spacer assembly	SR	Steel	Helium	Creep	Change in dimensions	No	3.2.1.6
				Radiation embrittlement	Cracking	No	3.2.1.9
Damaged fuel can top lid assembly (W74 Canister)	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can top lid assembly hardware (W74 Canister)	SR	Stainless steel	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Damaged fuel can guide tube assembly (W74 Canister)	SR	Stainless steel (welded)	Helium	Thermal aging	Loss of fracture toughness and loss of ductility	No	3.2.2.8
		Stainless steel	Helium	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Creep	Change in dimensions	No	3.2.2.6

Table 4-21 FuelSolutions^{TM} canister

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Damaged fuel can guide tube assembly (W74 Canister)	SR	Stainless steel	Helium	Radiation embrittlement	Cracking	No	3.2.2.9
Damaged fuel can neutron absorber (W74 Canister)	CR	Borated stainless steel	Helium	Boron depletion	Loss of criticality control	No; a TLAA may be required	3.4.1.1
				Thermal aging	Loss of fracture toughness and loss of ductility	No	3.4.1.3
				Creep	Change in dimensions	No	3.4.1.2
				Radiation embrittlement	Loss of fracture toughness and loss of ductility	No	3.4.1.4

Table 4-22 FuelSolutions^{TM} storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell, shear key	SH, SR*	Concrete, grout	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperature	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-22 FuelSolutions™ storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Concrete shell, shear key	SH, SR	Concrete	Air—outdoor	Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
Concrete shell	SH, SR	Reinforcing steel	Air—outdoor, groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6

Table 4-22 FuelSolutions^{TM} storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Steel liner, shield ring	SH, SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Embedded (concrete)	Radiation embrittlement	Cracking	No	3.2.1.9
Thermal shield	TH	Aluminum	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.3.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.3.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.3.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.3.4
				Thermal aging	Loss of strength	No	3.2.3.7
				Creep	Change in dimensions	No	3.2.3.5
				Radiation embrittlement	Cracking	No	3.2.3.8

Table 4-22 FuelSolutions^{TM} storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Shear lug, thermal shield support lug	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Support rail, guide rail	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.2.11
Canister support tube	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-22 FuelSolutions™ storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Tie rod, tie rod plate	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
Tie rod hardware	SR	Stainless steel	Sheltered	Stress corrosion cracking	Cracking	No	3.2.2.5
				Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
		Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Galvanic corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.3
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4

Table 4-22 FuelSolutions™ storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Tie rod hardware	SR	Steel	Sheltered	Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
Ram anchor	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
Top cover assembly	SR	Steel	Air—outdoor	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
			Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2

Table 4-22 FuelSolutions^{TM} storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top cover assembly	SR	Steel	Sheltered	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9
		Concrete	Embedded (steel)	Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Cracking	No	3.5.1.13
					Loss of strength	No	3.5.1.13
				Radiation damage	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.9
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.9
				Reaction with aggregates	Cracking	TLAA/AMP or a supporting analysis is required	3.5.1.3
					Loss of strength	TLAA/AMP or a supporting analysis is required	3.5.1.3
Top cover bolt	SR	Steel	Sheltered	General corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	External Surfaces Monitoring of Metallic Components AMP	3.2.1.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Radiation embrittlement	Cracking	No	3.2.1.9

Table 4-22 FuelSolutions™ storage cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top cover bolt	SR	Steel	Sheltered	Stress relaxation	Loss of preload	External Surfaces Monitoring of Metallic Components AMP	3.2.1.10
Coating on carbon steel components	SR	Coating	Air—outdoor	Radiation embrittlement	Coating degradation	TLAA/AMP or a supporting analysis is required	3.2.8
				Thermal aging	Coating degradation	TLAA/AMP or a supporting analysis is required	3.2.8
			Sheltered	Radiation embrittlement	Coating degradation	TLAA/AMP or a supporting analysis is required	3.2.8
				Thermal aging	Coating degradation	TLAA/AMP or a supporting analysis is required	3.2.8

Table 4-23 FuelSolutions™ transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Structural shell	SR*	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Inner liner	SR	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Neutron shield jacket, trunnion support plate, thermowell	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-23 FuelSolutions^{TM} transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield jacket, trunnion support plate, thermowell	SR	Stainless steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Neutron shield jacket support rib	SR	Stainless steel	Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Gamma shield	SH	Lead	Embedded (stainless steel)	None identified	None identified	No	3.2.6
Guide rail	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11

Table 4-23 FuelSolutions$^{\text{TM}}$ transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Top flange, bottom flange	SR	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Screw thread insert	SR	Stainless steel	Embedded (stainless steel)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Block	SR	Stainless steel	Embedded (stainless steel, lead)	Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Swagelok quick connect body, coupling, fitting, cap	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-23 FuelSolutions^{TM} transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Upper trunnion, lower trunnion	SR	Stainless steel (welded)	Air—indoor/outdoor	Stress corrosion cracking	Cracking	No	3.2.2.5
			Demineralized water	Stress corrosion cracking	Cracking	No	3.2.2.5
		Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
			Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Trunnion retainer, trunnion sleeve	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11

Table 4-23 FuelSolutions^{TM} transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Trunnion retainer, trunnion sleeve	SR	Stainless steel	Demineralized water	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
				Wear	Loss of material	Transfer Casks AMP	3.2.2.11
Trunnion bolt	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
				Stress relaxation	Loss of preload	No	3.2.2.10
Bolt for top cover, bottom cover, ram access cover	SR	Steel	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.1.1
				Pitting and crevice corrosion	Loss of material	Transfer Casks AMP	3.2.1.2
				Galvanic corrosion	Loss of material	Transfer Casks AMP	3.2.1.3

Table 4-23 FuelSolutions$^{\text{TM}}$ transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bolt for top cover, bottom cover, ram access cover	SR	Steel	Air—indoor/outdoor	Microbiologically influenced corrosion	Loss of material	No	3.2.1.4
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.1.9
				Stress relaxation	Loss of preload	No	3.2.1.10
Washer for trunnion, top cover, bottom cover, ram access cover	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Top cover, ram access cover	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-23 FuelSolutions™ transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Bottom cover	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Top lifting insert, bottom support ring	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9
Neutron shield plate	SR	Stainless steel	Air—indoor/outdoor	Pitting and crevice corrosion	Loss of material	No	3.2.2.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.2.4
				Stress corrosion cracking	Cracking	No	3.2.2.5
				Fatigue	Cracking	Evaluate design code TLAA, if applicable	3.2.2.7
				Radiation embrittlement	Cracking	No	3.2.2.9

Table 4-23 FuelSolutions^{TM} transfer cask

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Neutron shield plate	SR	Stainless steel	Embedded (RX-277, NS-3)	Radiation embrittlement	Cracking	No	3.2.2.9
Neutron shield	SH	RX-277, NS-3	Embedded (stainless steel)	Thermal aging	Loss of fracture Toughness and loss of ductility	No	3.3.1.2
				Radiation embrittlement	Cracking	No	3.3.1.3
				Boron depletion	Loss of shielding	TLAA/AMP or a supporting analysis is required	3.3.1.1
Coating on neutron shield jacket	TH	Coating	Air—indoor/outdoor	Radiation embrittlement	Coating degradation	TLAA/AMP or a supporting analysis is required	3.2.8
				Thermal aging	Coating degradation	TLAA/AMP or a supporting analysis is required	3.2.8
Pressure relief device	SR	Brass	Air—indoor/outdoor	General corrosion	Loss of material	Transfer Casks AMP	3.2.5.1
				Pitting and crevice corrosion	Loss of material	No	3.2.5.2
				Microbiologically influenced corrosion	Loss of material	No	3.2.5.3
				Radiation embrittlement	Cracking	No	3.2.5.4

4.7 Concrete pad

The support pad of an ISFSI is a reinforced concrete structure that provides a stable foundation for the DSSs and transfer equipment. Depending on the design basis of the system or site, the pad may be within the scope of renewal as an important-to-safety component or as a not-important-to-safety component, the failure of which could prevent the fulfillment of a fuction that is important-to-safety. Typically, the concrete pad is exposed to outdoor air and groundwater or soil environments and is designed and constructed in accordance with ACI codes and standards.

Table 4-24 provides a generic evaluation of potential aging mechanisms and effects requiring management for the concrete pad. The AMPs that provide an acceptable approach to managing the aging effects are also identified in the table.

Table 4-24 Concrete pad

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: ISFSI pad	SR*	Concrete	Air—outdoor	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-24 Concrete pad

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: ISFSI pad	SR	Concrete	Air—outdoor	Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
			Groundwater/soil	Aggressive chemical attack	Cracking	Reinforced Concrete Structures AMP	3.5.1.5
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.5

Table 4-24 Concrete pad

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: ISFSI pad	SR	Concrete	Groundwater/soil	Aggressive chemical attack	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.5
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.5
				Creep	Cracking	No	3.5.1.2
				Dehydration at high temperatures	Cracking	No	3.5.1.11
					Loss of strength	No	3.5.1.11
				Delayed ettringite formation	Loss of material (spalling, scaling)	No	3.5.1.13
					Loss of strength	No	3.5.1.13
					Cracking	No	3.5.1.13
				Differential settlement	Cracking	Reinforced Concrete Structures AMP	3.5.1.4
				Fatigue	Cracking	No	3.5.1.10
				Freeze and thaw	Cracking	Reinforced Concrete Structures AMP	3.5.1.1
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.1
				Microbiological degradation	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.12
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.12

Table 4-24 Concrete pad

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: ISFSI pad	SR	Concrete	Groundwater/soil	Microbiological degradation	Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.12
					Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.12
				Radiation damage	Cracking	No	3.5.1.9
					Loss of strength	No	3.5.1.9
				Reaction with aggregates	Cracking	Reinforced Concrete Structures AMP	3.5.1.3
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.3
				Salt scaling	Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.14
				Shrinkage	Cracking	No	3.5.1.7
				Leaching of calcium hydroxide	Loss of strength	Reinforced Concrete Structures AMP	3.5.1.8
					Increase in porosity and permeability	Reinforced Concrete Structures AMP	3.5.1.8

Table 4-24 Concrete pad

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Reinforced concrete: ISFSI pad	SR	Concrete	Groundwater/soil	Leaching of calcium hydroxide	Reduction of concrete pH (reducing corrosion resistance of steel embedments)	Reinforced Concrete Structures AMP	3.5.1.8
		Reinforcing steel	Air—outdoor; groundwater	Corrosion of reinforcing steel	Loss of concrete/steel bond	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of material (spalling, scaling)	Reinforced Concrete Structures AMP	3.5.1.6
					Cracking	Reinforced Concrete Structures AMP	3.5.1.6
					Loss of strength	Reinforced Concrete Structures AMP	3.5.1.6

4.8 Spent fuel assemblies

4.8.1 Spent fuel assembly description

Dry storage systems are designed to store a wide range of SNF assemblies in a dried and inerted (helium) atmosphere. This section provides a general description of the PWR and BWR spent fuel assembly components.

4.8.2 Fuel cladding and assembly hardware

Pressurized-water reactor fuel assemblies

While there are a number of fuel assembly design variants for PWRs, the assemblies mainly consist of the top nozzle, fuel rods, spacer grids, guide thimble tubes, and bottom nozzle. The various components of a typical 17 × 17 PWR fuel assembly are shown in Figure 4-30. Each fuel rod consists of enriched uranium dioxide pellets inserted into a cladding tube. The cladding tube is then capped with Zircaloy end plugs and seal welded at both ends to confine the fuel pellets and fission gases. The fuel cladding, fabricated from zirconium-based alloys, including Zircaloy-4, ZIRLO™, and M5®, provides a confinement barrier.

The structural support of the fuel assembly is provided by the top and bottom nozzles, the spacer grid assemblies, and the guide thimbles. Guide tubes, fabricated from zirconium-based alloys, are the main structural members of the fuel assembly. They also provide channels for neutron absorber rods and burnable poison rods. The bottom of the guide tube is fitted with an end plug with a flow port, which is then fastened into the bottom nozzle. Both the top and bottom nozzles are made of either stainless steel or Inconel, which also serve as structural members of the fuel assembly. The spacer grid assemblies provide support for the fuel cladding tubes. Two types of grid assemblies, fabricated from zirconium-based alloys or Inconel, are used in the fuel assemblies.

Boiling-water reactor fuel assemblies

Similar to the case for PWRs, there are a number of fuel assembly design variants for BWRs. The main components include the (i) upper tie plate, (ii) fuel rods, (iii) spacer grids, (iv) water rods, (v) channel, and (vi) lower tie plate, as shown in Figure 4-31 for the GE14 BWR fuel assembly in a 10 × 10 fuel rod array. Two types of fuel rods are used in the GE14 fuel bundles: standard rods and tie rods. The fuel rods are hollow cladding tubes fabricated from Zircaloy-2. Zircaloy end plugs are welded into place to seal the ends of the fuel rods. The tie rods differ from the standard fuel rods in that the end plugs are threaded into the tie plates. They hold the fuel bundle together and support the weight of the fuel bundle during fuel handling operations.

In the BWR fuel assembly, fuel bundles are enclosed in open-ended, square tubes (also called channels) and are supported at the ends of the fuel bundles by the upper and lower tie plates. The channels made of zirconium-based alloys are ducts for coolant flow that prevent lateral flow of coolant among the fuel assemblies operating at different power levels. Both the upper tie and lower tie plates are fabricated from stainless steel. The upper tie plate provides alignment and support for the fuel rods at the top of the fuel bundle, while the lower tie plate positions the fuel rods laterally. The spacer grids, fabricated from zirconium-based alloys or Inconel, hold the fuel rods in the proper location so that optimum fuel spacing is maintained.

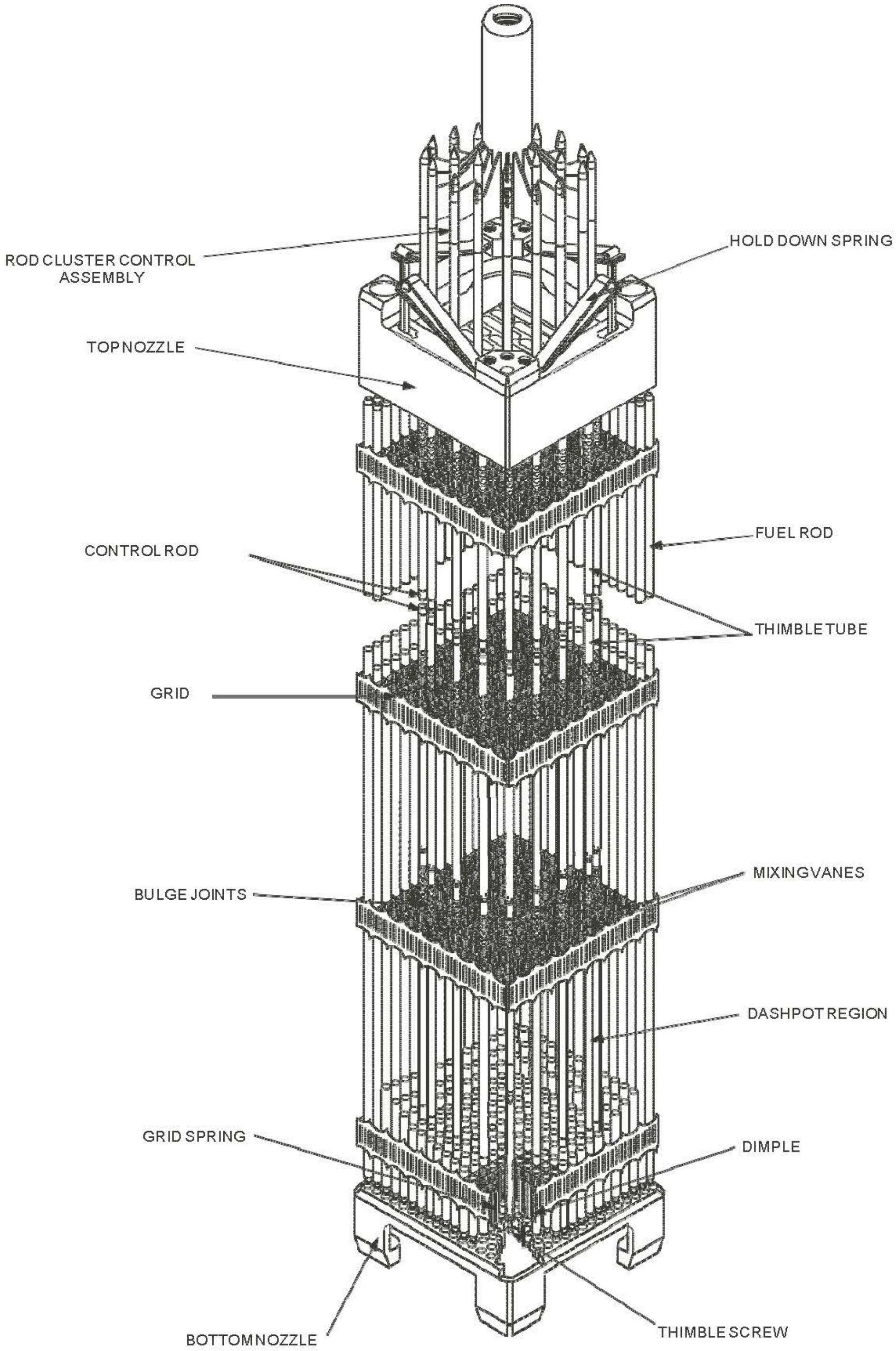


Figure 4-30 Typical pressurized-water reactor fuel assembly (NRC, 2002)

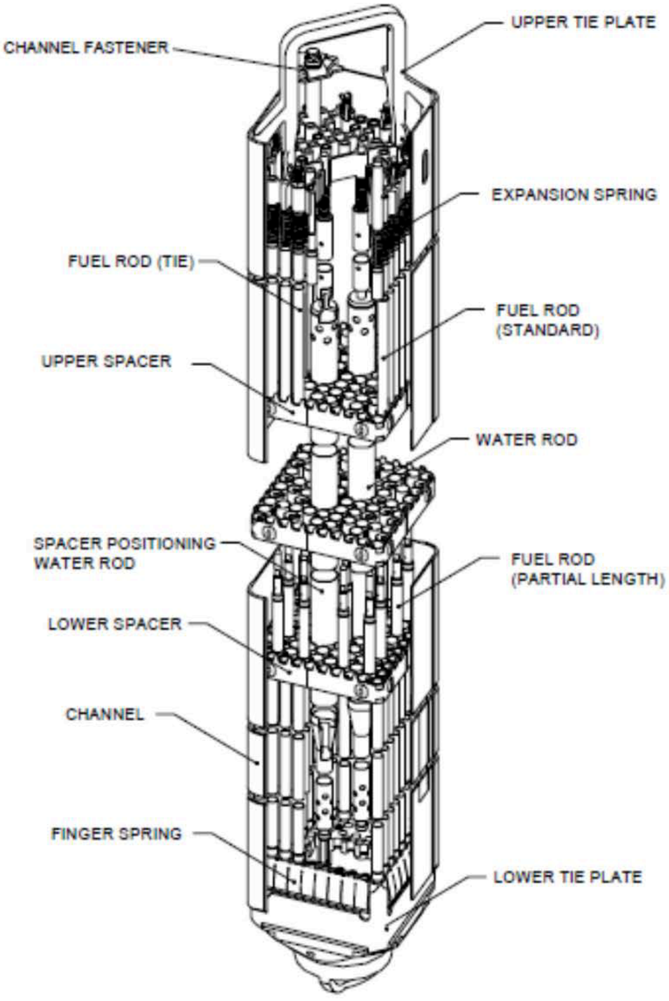


Figure 4-31 Boiling-water reactor GE14 fuel assembly (GNF, 2005)

Table 4-25 provides a generic evaluation of potential aging mechanisms and effects requiring management for specific components of the SNF assemblies. The AMPs that provide an acceptable approach to managing the aging effects are also identified in the table.

Table 4-25 Spent fuel assemblies

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel rod cladding	CO, CR, RE, SH, SR, TH*	Zirconium-based alloy (Zircaloy-2, Zircaloy-4, ZIRLO^{TM}, or M5$^{®}$)	Helium	Oxidation	Loss of load bearing capacity	No	3.6.1.6
				Pitting corrosion	Loss of material	No	3.6.1.7
				Galvanic corrosion	Loss of material	No	3.6.1.8
				Stress corrosion cracking	Cracking	No	3.6.1.9
				Hydride-induced embrittlement	Loss of ductility	No	3.6.1.1
				Delayed hydride cracking	Cracking	No	3.6.1.2
				Thermal Creep	Changes in dimensions	High-Burnup Fuel Monitoring and Assessment AMP	3.6.1.3
				Low-temperature creep	Changes in dimensions	No	3.6.1.4
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11
				Mechanical overload	Cracking	No	3.6.1.5
Guide tubes (PWR) or water channels (BWR)	RE, SR	Zirconium-based alloy	Helium	Creep	Changes in dimensions	No	3.6.2.1
				Hydriding	Changes in dimensions	No	3.6.2.2
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11
Spacer grids	CR, RE, SR, TH	Zirconium-based alloy	Helium	Creep	Changes in dimensions	No	3.6.2.1

*Safety Functions: Confinement (CO), Subcriticality (CR), Retrievability (RE), Radiation Shielding (SH), Structural Integrity (SR), Thermal/Heat Removal (TH)

Table 4-25 Spent fuel assemblies

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Spacer grids	CR, RE, SR, TH	Zirconium-based alloy	Helium	Hydriding	Changes in dimensions	No	3.6.2.2
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11
		Inconel	Helium	Creep	Change in dimensions	No	3.6.2.1
				General corrosion	Loss of material	No	3.6.2.3
				Stress corrosion cracking	Cracking	No	3.6.2.4
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11
Lower and upper end fittings	CR, RE, SR	Stainless steel	Helium	Creep	Change in dimensions	No	3.6.2.1
				General corrosion	Loss of material	No	3.6.2.3
				Stress corrosion cracking	Cracking	No	3.6.2.4
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11
		Inconel	Helium	Creep	Change in dimensions	No	3.6.2.1
				General corrosion	Loss of material	No	3.6.2.3
				Stress corrosion cracking	Cracking	No	3.6.2.4
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11

Table 4-25 Spent fuel assemblies

Structure, System, or Component	Intended Safety Function	Material	Environment	Aging Mechanism	Aging Effect	Aging Management	Technical Basis (Section)
Fuel channel (BWR)	CR, TH	Zirconium-based alloy	Helium	Creep	Change in dimensions	No	3.6.2.1
				Hydriding	Change in dimensions	No	3.6.2.2
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11
Poison rod assemblies (PWR)	CR	Stainless steel	Helium	Creep	Change in dimensions	No	3.6.2.1
				General corrosion	Loss of material	No	3.6.2.3
				Stress corrosion cracking	Cracking	No	3.6.2.4
				Radiation embrittlement	Loss of strength	No	3.6.1.10
				Fatigue	Cracking	No	3.6.1.11

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5 TIME-LIMITED AGING ANALYSES

5.1 Introduction

Renewal applicants are required to reevaluate all aging-related calculations or analyses involving time-limited assumptions that were contained in the original design basis (e.g., fatigue analyses, corrosion wastage calculations). These evaluations are designated as time-limited aging analyses (TLAAs), and Title 10 of the *Code of Federal Regulations* (10 CFR) 72.3, "Definitions," defines them as those calculations and analyses meeting all six of the following criteria:

(1) Involve SSCs important to safety within the scope of the specific-license renewal, as delineated in Subpart F of 10 CFR Part 72, or within the scope of the spent fuel storage CoC renewal, as delineated in Subpart L of 10 CFR Part 72, respectively.

(2) Consider the effects of aging.

(3) Involve time-limited assumptions defined by the current operating term.

(4) Were determined to be relevant by the specific licensee or certificate holder in making a safety determination.

(5) Involve conclusions or provide the basis of conclusions related to the capability of SSCs to perform their intended safety functions.

(6) Are contained or incorporated by reference in the design bases.

5.2 Review

NUREG-1927, Revision 1, "Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel" (NRC, 2016), provides detailed staff guidance for the review of TLAAs.

The NRC reviewer should use the final safety analysis report (FSAR) and other documents that detail the design bases and confirm that the renewal applicant did not omit any TLAAs submitted as part of the approved design bases. In some cases, the original analyses may have been performed as part of a code design but not explicitly discussed in the FSAR. Thus, the reviewer must identify and review any design codes and standards associated with a storage system to ensure that any required analyses are captured in the applicant's TLAAs. Table 5-1 identifies some examples of fatigue analyses that are incorporated into the design codes for the dry storage system designs this report evaluates.

The reviewer also should ensure that the applicant addresses any design basis calculations that use materials properties that may be time dependent. For example, aluminum alloys used in some fuel baskets can lose strength over time at elevated temperatures (see Section 3.2.3.7), and this may affect the performance of the fuel basket in a cask tipover analysis. If the original design basis calculations did not adequately account for such material property changes through the period of extended operation, the analyses should be updated.

The reviewer should ensure that the applicant has appropriately dispositioned an identified TLAA by using one of the following methods:

- Demonstrate that the existing analysis remains valid for the period of extended operation, has already considered the requested period of extended operation, and concludes that the structure, system, or component (SSC) will continue to perform its intended function through the end of the requested period of extended operation.

- Revise or update the existing analysis to demonstrate that it has been projected to the end of the requested period of extended operation and concludes that the SSC will continue to perform its intended function through the end of the requested period of extended operation.

- Manage the effects of aging on the SSC for the requested period of extended operation through an aging management program.

Table 5-1 Examples of fatigue analyses contained within storage system design bases

System	SSC	Fatigue Evaluation Criteria (ASME Code Section III, Division 1 (ASME, 2007))
Standardized and Advanced NUHOMS®*	DSC Confinement	NB-3222.4
	Transfer Cask	NC-3219
HI-STORM 100, HI-STAR 100	MPC Confinement	NB-3222.4
	Fuel Basket	NG-3222.4
	HI-STAR Overpack Helium Boundary	NB-3222.4
TN-32 & 68	Confinement Boundary	NB-3222.4
	Fuel Basket	NB-3222.4
NAC-UMS, MPC, and MAGNASTOR	Canister Confinement	NB-3222.4
	Fuel Basket	NG-3222.4
FuelSolutions™	Canister Confinement	NB-3222.4
	Fuel Basket	NG-3222.4
	Transfer Cask	NC-3219

5.3 References

NRC. NUREG–1927, “Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel.” Revision 1. Washington, DC: U.S. Nuclear Regulatory Commission. ADAMS Accession No. ML16179A148. 2016.

ASME. Boiler and Pressure Vessel Code, Section III, Division 1, “Rules for Construction of Nuclear Facility Components,” Division 1, Subsection NB, “Class 1 Components,” Subsection NC, “Class 2 Components,” and Subsection NG, “Core Support Structures”; American Society of Mechanical Engineers. 2007.

6 EXAMPLE AGING MANAGEMENT PROGRAMS

6.1 Introduction

The example aging management programs (AMPs) presented in this chapter and listed in Table 6-1 below describe a generically acceptable approach to managing the credible aging effects that were identified in the technical bases discussions in Chapter 3 and the aging management review tables in Chapter 4. AMPs monitor and control the degradation of structures, systems, and components (SSCs) within the scope of renewal, so that aging effects will not result in a loss of intended functions during the period of extended operation. An AMP includes all activities that are credited for managing aging mechanisms or effects for specific SSCs. An effective AMP prevents, mitigates, or detects the aging effects and provides for the prediction of the extent of the effects of aging and timely corrective actions before there is a loss of intended function.

If an applicant credits these generic AMPs in the renewal application, the NRC staff should ensure that the applicant demonstrates that the design features, environmental conditions, and operating experience for the subject independent spent fuel storage installation (ISFSI) or dry storage system (DSS) are bounded by those evaluated in this report. Otherwise, the staff should ensure that the applicant augments the AMPs as appropriate to address the impact of unique design or operating parameters.

Table 6-1 Example aging management programs

Section	AMP
6.5	Localized Corrosion and Stress Corrosion Cracking of Welded Stainless Steel Dry Storage Canisters
6.6	Reinforced Concrete Structures
6.7	External Surfaces Monitoring of Metallic Components
6.8	Ventilation Systems
6.9	Bolted Cask Seal Leakage Monitoring
6.10	Transfer Casks
6.11	High-Burnup Fuel Monitoring and Assessment

6.2 Alternative approaches

An applicant may propose alternative approaches to manage the effects of aging. In its review of alternative AMPs, the staff should use the guidance in NUREG–1927, Revision 1, “Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel” (NRC, 2016). As described in greater detail in NUREG–1927, an AMP generally should contain the following 10 elements:

(1) Scope of program: the specific SSCs and subcomponents covered by the AMP and the intended functions to be maintained, in addition to stating the specific materials, environments, and aging mechanisms and effects to be managed

(2) Preventive actions: actions to prevent aging or mitigate the rates of aging for SSCs

(3) Parameters monitored or inspected: the specific parameters that will be monitored or inspected and a description of how those parameters will be capable of identifying degradation before a loss of intended function

(4) Detection of aging effects: the inspection and monitoring details, including method or technique, frequency, sample size, data collection, and timing of inspections

(5) Monitoring and trending: how data will be evaluated and trended to ensure timely corrective actions

(6) Acceptance criteria: the criteria against which the need for corrective action will be evaluated

(7) Corrective actions: The measures to be taken when the acceptance criteria are not met, including root cause determination and prevention of recurrence, as appropriate

(8) Confirmation process: processes in place to verify that preventive actions are adequate and that appropriate corrective actions have been completed and are effective

(9) Administrative controls: processes in place that provide a formal review and approval process for activities related to the AMP (e.g., inspector requirements, instrument calibration)

(10) Operating experience: a review of operational experience that supports the determination that the AMP is capable of maintaining SSC functions in the period of extended operation

The reviewer should examine the applicant's proposed 10 elements to verify that the program is capable of managing the specific aging mechanisms and effects identified by the aging management review (AMR). The reviewer should recognize that an applicant may develop AMPs following a different format or style. For such reviews, the NRC staff should ensure that sufficient detail (i.e., supporting technical bases) is provided in the alternative format in comparison with the 10 AMP elements of this guidance.

An applicant may credit existing site maintenance and inspection activities to manage the effects of aging. In such cases, the reviewer should ensure that the design basis documentation describes those activities with sufficient detail ensure that the 10 AMP elements are fully addressed.

6.3 Learning aging management

As described in NUREG–1927, the reviewer should ensure that the application includes provisions to conduct periodic future reviews of operating experience to confirm the effectiveness of the AMPs or identify a need to enhance or modify an AMP. The reviewer also should verify that the applicant: (1) references a specific system to be used to obtain, aggregate, and enter site-specific, design-specific, and industrywide operating experience, and (2) discusses how it intends to provide timely reporting of operating experience to this system.

If an applicant follows this approach, the reviewer should ensure that the description of the periodic assessments includes specific performance criteria (e.g., program-specific performance indicators for each of the 10 AMP elements) and proposed actions based on the assessment findings. The reviewer should also ensure that the timing of the assessments appropriately considers the rate of aging degradation and the anticipated availability of data from industry initiatives.

Nuclear Energy Institute (NEI) 14-03, “Format, Content, and Implementation Guidance for Dry Cask Storage Operations-Based Aging Management,” Revision 2, provides a proposed framework for learning AMPs through the use of “tollgates” (NEI, 2016). NEI 14-03 defines “tollgates” as periodic points within the period of extended operation when licensees would be required to evaluate aggregate feedback and perform and document a safety assessment that confirms the safe storage of spent fuel. At the time of publication of this report, the NRC staff was continuing its review of NEI 14-03, Revision 2, for proposed NRC endorsement. However, until a time when NEI 14-03 may be endorsed by the NRC, Section 3.6.1.10 of NUREG–1927, Revision 1, provides guidance to reviewers on ensuring AMP effectiveness.

6.4 References

NEI. “Format, Content and Implementation Guidance for Dry Cask Storage Operations-Based Aging Management for Dry Cask Storage.” NEI 14-03, Rev. 2. ADAMS Accession No. ML16356A210. Nuclear Energy Institute. 2016.

NRC. NUREG–1927, “Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel.” Revision 1. Washington, DC: U.S. Nuclear Regulatory Commission. 2016.

6.5 Localized Corrosion and Stress Corrosion Cracking of Welded Stainless Steel Dry Storage Canisters

Welded stainless steel canisters are used in the majority of the DSSs in the United States for spent nuclear fuel (SNF) from commercial power reactors at both specific-licensed and general-licensed ISFSIs. The welded stainless steel canisters are the primary confinement boundary during storage. While there are no known operational occurrences of aging or localized corrosion of welded stainless steel canisters, operational experience with nuclear reactors that were located close to an open ocean or bay has shown that pitting corrosion, crevice corrosion, and chloride-induced stress corrosion cracking (CISCC) can occur in welded stainless steel components as a result of atmospheric deposition and deliquescence of chloride-containing salts. Laboratory and natural exposure tests suggest that CISCC can occur with sufficient surface chloride concentrations and that, with those concentrations of chloride, crack propagation rates can be of engineering significance for welded stainless steel canisters during the period of extended operation.

Based on reactor operating experience, as well as laboratory and field testing, localized corrosion and CISCC are potential aging mechanisms for welded stainless steel canisters. Environments where chloride-containing salts may be deposited on welded stainless steel canisters include coastal locations near salt water and locations that are close to cooling towers or roads that are salted. The Electric Power Research Institute (EPRI) has developed aging management guidance to address the potential for CISCC of welded stainless steel canisters (Fuhr et al., 2017). In addition, the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), Section XI, has formed a task group to develop a code case to establish the requirements for inservice inspection and acceptance criteria for DSS canisters (Code Case N-860) that may follow the recommendations of the EPRI aging management guidance. However, the development of a consensus-based code case for inservice inspection of DSS canisters may take several years to complete. To address potential aging effects as a result of localized corrosion cracking and stress corrosion cracking (SCC) in the absence of an acceptable code case, the NRC has provided an example AMP for welded stainless steel canisters used in DSSs that relies on guidance from consensus codes for inservice inspection of nuclear power plant components. Elements of an NRC staff-developed example AMP are described in Table 6-2.

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters

Element	Description
1. Scope of Program	Inspection of welded stainless steel dry storage canister confinement boundary external surfaces for atmospheric deposits, localized corrosion, and SCC. Examinations should be focused on areas with the following attributes: • canister fabrication welds and weld heat affected zones • closure welds and weld heat affected zones • areas of the canister to which temporary supports or attachments were attached by welding and subsequently removed • locations where a crevice is formed on the canister surface • horizontal (±30°) surfaces where deposit accumulation may accumulate at a faster rate compared to vertical surfaces • canister surfaces that are cold relative to the average surface temperature • canister surfaces with higher amounts of atmospheric deposits Effort should be made to identify and prioritize examinations of areas on canisters that have two or more of the above attributes (e.g., canister surface that is cold relative to average surface temperature and also has a weld or weld heat affected zone).
2. Preventive Actions	None; AMP is for condition monitoring. However, DSS canister designs may include preventive actions such as fabrication procedures and surface modification methods to impart compressive residual stresses on the canister welds and weld heat-affected zones to reduce the potential for SCC. Preventive actions may also include the use of DSS canister confinement boundary materials that are resistant to localized corrosion and SCC. For such cases the preventive actions described should be supported with an analysis and data demonstrating the preventive actions are effective.
3. Parameters Monitored/ Inspected	Parameters monitored or inspected should include: • visual evidence of discontinuities and imperfections such as localized corrosion, including pitting corrosion, crevice corrosion and SCC of the canister welds and weld heat-affected zones • size and location of localized corrosion and SCC • appearance and location of deposits on the canister surfaces
4. Detection of Aging Effects	Visually examine deposits on the canister surfaces and identify corrosion products that may be indicators of localized corrosion and SCC in the welds and weld heat-affected zones. Visual examination instrumentation with demonstrated sizing and depth measurement

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	capability may be useful in the determination of the size and depth of pits open to the surface. Visual examination may also detect the presence of cracks originating from pits. However, the ability to detect cracks on clean metal surfaces using visual examination methods is dependent on several factors and can be difficult for tight crack opening displacements (Cumblidge et al., 2004, 2007). The presence of significant corrosion product accumulation may also interfere with the identification of SCC using visual examination methods. Volumetric examination is necessary to characterize SCC. Volumetric examination of pits and areas immediately adjacent to pits is necessary when pits are located within 25 mm [1 in] of a through thickness weld or within 25 mm [1 in] of an area where an temporary attachment was known to be located. <u>Visual Examination</u> Pitting and crevice corrosion that is open to the surface can potentially be detected by visual testing (ASME Code Section V, Table A-110). Because of the high neutron and gamma radiation fields near the surface of the stainless steel dry storage canisters, direct visual examination is not possible. Procedures for remote visual examination should be performance demonstrated; procedure attributes, for example, equipment resolution and lighting requirements, should reference applicable standards, such as ASME Code Section XI, Article IWA-2200 for VT-1 and VT-3 examinations (ASME, 2007) and BWRVIP-03 (Selby, 2005) for EVT-1 examinations. <u>Volumetric Examination</u> Additional assessment is necessary for suspected areas of localized corrosion and SCC. In these cases, the severity of degradation must be assessed, including the dimensions of the affected area and the depth of penetration with respect to the thickness of the canister. For accessible areas where adequate cleaning can be performed, remote visual examination meeting the requirements for VT-1 Examination (ASME Code Section XI, IWA-2211) may be used to determine the type of degradation present (e.g., pitting corrosion or SCC) and the location of degradation. Examinations to characterize the extent and severity of localized corrosion and SCC should be conducted using surface or volumetric examination methods consistent with the requirements of ASME Code Section XI, IWB-2500, for category B-J components (ASME, 2007).

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	<u>Sample Size</u> For sites where inspections are necessary, there should be a minimum of one canister at each site. Preference should be given to the canisters with the greatest susceptibility for localized corrosion or SCC. Factors to be considered include older and colder canisters with the greatest potential for the accumulation and deliquescence of deposited salts that may promote localized corrosion and SCC, types of systems used at the site, canister location with respect to potential sources of atmospheric deposits, system design, and operational experience. Industry guidance on evaluating susceptibility has been published by the EPRI (Fuhr et al., 2015). Justification for not conducting inspections for localized corrosion or SCC should be provided on a case-by-case basis for each ISFSI site where welded stainless steel canisters are in use. Acceptable justification may be based on a comparison of susceptibility for the ISFSI location versus at least two other ISFSI sites determined to have greater susceptibility but that showed no evidence of localized corrosion or SCC in inspections completed within 5 years of the time of the assessment. The justification must consider the full range of available ISFSI susceptibility assessments and welded stainless steel canister examination results. <u>Data Collection</u> Canister Examination: documentation of the examination of the canister, location, and appearance of deposits and an assessment of the suspect areas where corrosion products were observed as described in corrective actions Bounding Analysis: a complete listing of other sites considered, susceptibility assessments for those sites, and results of examinations conducted at those sites, as well as a justification for not including other sites where examinations showed evidence of localized corrosion or SCC <u>Frequency</u> The frequency of inspection should be determined based on the localized corrosion and SCC susceptibility of both the site and the canisters in service, aggregated operational experience of similar storage system canisters and previous site specific examination results

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	<u>Timing of Inspections</u> The timing of the inspections includes the preapplication inspection or general-licensee baseline inspection, performed per Sections 3.4.1.2 and 3.6.1.10 of NUREG–1927, Revision 1, and at the frequency specified by the AMP. Alternative detection methods or techniques may be provided. For these cases: • The method or technique should be adequate and proven to be capable of evaluating the condition of the external surface of the canister against the acceptance criteria for the detection of localized corrosion and SCC. • The proposed intervals for inspection or monitoring are consistent with applicable site-specific, design-specific, or industrywide operating experience and should have sufficient frequency to ensure that the confinement function will be maintained until the next scheduled inspection. • The data collection methods should be sufficient for evaluating localized corrosion and SCC and should reference specific methods to be used for data acquisition, including any applicable consensus codes and standards.
5. Monitoring and Trending	Monitoring and trending methods are in accordance with ASME Code Section XI evaluation criteria. Monitoring and trending methods reference plans/procedures are used to do the following: • Establish a baseline before or at the beginning of the period of extended operation • Track trending of parameters or effects not corrected following a previous inspection including — the locations and size of any areas of localized corrosion or SCC — the disposition of canisters with identified aging effects and the results of supplemental canister inspections Monitoring and trending should also include: • the appearance of the canister, particularly at welds and in crevice locations, documented with images and video that will allow comparison in subsequent examinations

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	• changes to the size and number of any rust-colored stains as a result of iron contamination of the surface in subsequent inspections
6. Acceptance Criteria	No indications of localized corrosion pits, etching, crevice corrosion, SCC, red-orange-colored corrosion products emanating from crevice locations, or red-orange-colored corrosion products in the vicinity of canister fabrication welds, closure welds, and welds associated with temporary attachments during canister fabrication. Flaws identified must be assessed in accordance with the acceptance standards identified in ASME B&PV Code Section XI, IWB-3514. <u>Indications Requiring Additional Evaluation</u> Confirmed or suspected areas of crevice corrosion, pitting corrosion, and SCC must be assessed in accordance with the acceptance criteria identified in ASME B&PV Code Section XI, IWB-3640. Although shop and handling procedures include controls to prevent iron contamination of the stainless steel surfaces, contamination does occur and is usually identified by rust-colored surface deposits. Iron contamination can exacerbate CISCC in stainless steels. In accessible locations, removal of the deposits and rust stains that reveal undamaged welds (i.e., absence of pits, crack, localized attack, or etching) and the original machining/grinding marks on the stainless steel base metal, including weld heat-affected zones, may be used to confirm that localized corrosion or SCC has not been initiated. Indications of interest that are subject to additional examination and disposition include: • localized corrosion pits, crevice corrosion, SCC, and etching (note that these indications may be covered by obstructions (i.e., crevices)); deposits; or corrosion products • discrete red-orange-colored corrosion products that are 1 mm [0.039 in] in diameter or larger, in SCC susceptible locations on the canister surface that includes areas adjacent to fabrication welds, closure welds, locations where temporary attachments may have been welded to and subsequently removed from the stainless steel dry storage canister, and the weld heat-affected zones • linear appearance of any color of corrosion products of any size parallel to or traversing fabrication welds, closure welds, locations where temporary attachments may have been welded to and subsequently removed from the stainless steel dry

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters

Element	Description
	storage canister, and the weld heat-affected zones of these areas • red-orange-colored corrosion products greater than 1 mm [0.039 in] in diameter or red-orange-colored corrosion tubercles of any size combined with deposit accumulations in SCC susceptible locations on the stainless steel canister • red-orange-corrosion products present at the mouth of a crevice that includes a portion of the canister surface Alternative acceptance criteria may be provided. For such cases, the acceptance criteria should: • include a quantitative basis (justifiable by operating experience, engineering analysis, consensus codes/standards) • avoid the use of nonquantifiable phrases (e.g., significant, moderate, minor, little, slight, few) • be achievable and clearly actionable
7. Corrective Actions	Results that do not meet the acceptance criteria are addressed as conditions adverse to quality or significant conditions adverse to quality under those specific portions of the specific- or general-licensee quality assurance (QA) program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that corrective actions are completed within the specific- or general-licensee's Corrective Action Program (CAP), and include provisions to • perform functionality assessments • perform apparent cause evaluations and root cause evaluations • address the extent of condition • determine actions to prevent recurrence for significant conditions adverse to quality; ensure justifications for nonrepairs • trend conditions • identify operating experience actions, including modification to the existing AMP (e.g., increased frequency) • determine if the condition is reportable to the NRC per 10 CFR 72.75 <u>Extent of Condition</u> Confirmation of localized corrosion or SCC may warrant inspection of additional canisters at the same ISFSI location to determine the extent of condition. Priority for additional inspections should be to canisters with similar time in service and initial loading. Canisters with confirmed localized corrosion or SCC must be evaluated for continued service. Canisters with localized corrosion or SCC that do

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	not meet the prescribed evaluation criteria are not permitted to remain in service without an engineering analysis or mitigation actions.
8. Confirmation Process	The confirmation process will be commensurate with the specific or general licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B. The QA program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality. The confirmation process describes or references procedures to: • determine followup actions to verify effective implementation of corrective actions • monitor for adverse trends due to recurring or repetitive findings or observations
9. Administrative Controls	The administrative controls are in accordance with the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that administrative controls include provisions that define: • instrument calibration and maintenance • inspector requirements • record retention requirements • document control The administrative controls describe or reference: • methods for reporting results to NRC per 10 CFR 72.75 • frequency for updating an AMP based on site-specific, design-specific, and industrywide operational experience
10. Operating Experience	The AMP references and evaluates applicable operating experience, before renewal, and will continue to do so as new operating experience is developed and made available after renewal, including: • internal and industrywide condition reports • internal and industrywide corrective action reports • vendor-issued safety bulletins • NRC generic communications • applicable U.S. Department of Energy (DOE) or industry initiatives (e.g., EPRI- or DOE-sponsored inspections) The AMP clearly identifies any degradation in the referenced operating experience as either age related or event driven, with

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	proper justification for that assessment. Past operating experience supports the adequacy of the proposed AMP, including the method/technique, acceptance criteria, and frequency of inspection. The AMP references the methods for capturing operating experience from other ISFSIs with similar in-scope SSCs. CISCC of austenitic stainless steels is a known degradation mechanism for aqueous environments; however, operational experience in aqueous environments is not directly applicable in assessing the potential for atmospheric CISCC for austenitic stainless steel dry storage canisters. Atmospheric CISCC of austenitic stainless steels has been reported in a range of industries, including welded stainless steel components and piping in operating nuclear power plants. <u>Spent Fuel Storage</u> Inspections of dry storage canisters after 20 years in service have been conducted at a few ISFSI sites. Details of the inspection conducted at nuclear power plant ISFSIs are documented in EPRI and Sandia National Laboratories reports (Waldrop et al., 2016; 2014; Bryan and Enos, 2014). No evidence of localized corrosion was identified but some amount of chloride-containing salts were determined to be present and corrosion products believed to be related to iron contamination were identified at the Calvert Cliffs ISFSI. <u>Operating Power Reactors</u> NRC Information Notice 2012-20 (NRC, 2012) documents previous cases of atmospheric CISCC of welded stainless steel piping systems and tanks at operating reactor locations. Atmospheric CISCC growth rates determined from operational experience at both domestic and foreign nuclear power plants, including events at San Onofre, Turkey Point, St. Lucie, and Koeberg (South Africa), range from 3.6×10^{-12} m/sec to 2.9×10^{-11} m/sec for components at ambient temperatures. <u>Relevant Literature and Testing</u> EPRI has recently conducted a literature review of CISCC that summarizes the results of many previous laboratory investigations (Gorman et al., 2014). The NRC has recently published the results of a completed investigation of CISCC testing of type 304, 304L, and 316L stainless

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	steel and welds (He et al., 2014). This study indicates that SCC was initiated at stresses just above the yield strength in tests conducted using 304 stainless steel C-ring specimens. Testing with U-bend specimens showed that CISCC was observed with the lowest simulated sea salt concentrations tested (100 mg salt/m^2 or ~55 mg chloride/m^2) at temperatures of 52 degrees C [125.6 degrees F] using a maximum absolute humidity of 30 g/m^3, which is generally accepted as being near the maximum absolute humidity in a natural environment. Both laboratory and field investigations have been conducted by CRIEPI and TEPCO. This includes the early work by Tokiwai et al. (1985), who reported the critical surface chloride concentrations of 8 mg/m^2 for CISCC on sensitized 304 stainless steel. Kosaki (2008) reported crack growth rates of 9.6×10^{-12} m/sec obtained in natural exposure tests on Miyakojima Island with type 304 base metals and welds, type 304L welds, and type 316LN welds. Hayashibara et al. (2008) reported activation energy for crack growth in type 304 stainless steel of 5.6 to 9.4 kcal/mol [23 to 39 kJ/mol], based on testing conducted at temperatures of 50 to 80 degrees C [122 to 176 degrees F].
References	ASME. “Boiler and Pressure Vessel Code Section XI—Rules for Inservice Inspection of Nuclear Power Plant Components.” New York, New York: American Society of Mechanical Engineers. 2007. Bryan, C.R. and D.G. Enos. SAND2014-16383, “Analysis of Dust Samples Collected From Spent Nuclear Fuel Interim Storage Containers at Hope Creek, Delaware, and Diablo Canyon, California.” Albuquerque, New Mexico: Sandia National Laboratories. July 2014. Cumblidge, S.E., M.T. Anderson, and S.R. Doctor. NUREG/CR-6860, “An Assessment of Visual Testing.” ADAMS Accession No. ML043630040. Richland, Washington. Pacific Northwest National Laboratory. 2004. Cumblidge, S.E., M.T. Anderson, S.R. Doctor, F.A. Simonen, and A.J. Elliot. NUREG/CR-6943, “A Study of Remote Visual Methods to Detect Cracking in Reactor Components.” ADAMS Accession No. ML073110060. Richland, Washington. Pacific Northwest National Laboratory. 2007. Fuhr, K., J. Broussard, and G. White. “Susceptibility Assessment Criteria for Chloride-Induced Stress Corrosion Cracking (CISCC) of Welded Stainless Steel Canisters for Dry Cask Storage Systems.”

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	EPRI-3002005371. Palo Alto, California: Electric Power Research Institute. 2015. Fuhr, K., J. Broussard, and G. White. "Aging Management Guidance to Address Potential Chloride-Induced Stress Corrosion Cracking of Welded Stainless Steel Canisters," EPRI-3002008193. Palo Alto, California: Electric Power Research Institute. 2017. Gorman, J., K. Fuhr, and J. Broussard. "Literature Review of Environmental Conditions and Chloride-Induced Degradation Relevant to Stainless Steel Canisters in Dry Cask Storage Systems." EPRI-3002002528. Palo Alto, California: Electric Power Research Institute. 2014. Hayashibara, H., M. Mayuzumi, Y. Mizutani, and J. Tani. "Effect of Temperature and Humidity on Atmospheric Stress Corrosion Cracking of Stainless Steel." *Corrosion 2008*. Paper 08492, Houston, Texas: NACE International. 2008. He, X., T.S. Mintz, R. Pabalan, L. Miller, and G. Oberson. "Assessment of Stress Corrosion Cracking Susceptibility for Austenitic Stainless Steels Exposed to Atmospheric Chloride and Non-Chloride Salts." NUREG/CR-7170. ADAMS Accession No. ML14051A417. Washington, DC. U.S. Nuclear Regulatory Commission, February 2014, Kosaki, A. "Evaluation Method of Corrosion Lifetime of Conventional Stainless Steel Canister Under Oceanic Air Environment." *Nuclear Engineering and Design*. Vol. 238. pp.1,233–1,240. 2008. NRC. "Information Notice 2012-20: "Potential Chloride-Induced Stress Corrosion Cracking of Austenitic Stainless Steel and Maintenance of Dry Cask Storage System Canisters." ADAMS Accession No. ML12319A440. Washington, DC: U.S. Nuclear Regulatory Commission. 2012. Selby, G. "BWR Vessel and Internals Project, Reactor Pressure Vessel and Internals Examination Guidelines." EPRI 1011689, TR-105696-R8 (BWRVIP-03) Rev. 8. Palo Alto, California: Electric Power Research Institute. 2005. Tokiwai, M., H. Kimura, and H. Kusanagi. "The Amount of Chlorine Contamination for Prevention of Stress Corrosion Cracking in Sensitized Type 304 Stainless Steel." *Corrosion Science*. Vol. 25, Issue 8–9. pp. 837–844. 1985.

Table 6-2 Example aging management program for Localized Corrosion And Stress Corrosion Cracking Of Welded Stainless Steel Dry Storage Canisters	
Element	**Description**
	Waldrop, K., C. Bryan, D. Enos, “Diablo Canyon Stainless Steel Dry Storage Canister Inspection,” EPRI-3002002822, Palo Alto, CA: EPRI, 2016. Waldrop, K., W. Bracey, K. Morris, C. Bryan, and D. Enos. “Calvert Cliffs Stainless Steel Dry Storage Canister Inspection.” EPRI-1025209. Palo Alto, California: Electric Power Research Institute. 2014.

6.6 Reinforced Concrete Structures

An example AMP for reinforced concrete structures is provided below. The AMP consists of condition monitoring, performance monitoring, and mitigation and prevention activities. The program includes periodic visual inspections by personnel qualified to monitor reinforced concrete for applicable aging effects, such as those described in the American Concrete Institute (ACI) guides ACI 349.3R-02, ACI 201.1R-08, and American National Standards Institute/American Society of Civil Engineers guidelines (ANSI/ASCE) 11-99. Identified aging effects are evaluated against acceptance criteria derived from the design bases or industry guides and standards, including ACI 349, ACI 318, ACI 349.3R-02 and ASME Code Section XI, Subsection IWL.

The program also includes periodic sampling and testing of groundwater and the need to assess the impact of any changes in its chemistry on below-grade concrete structures. Additional activities include radiation surveys to ensure the shielding functions of the concrete structure are maintained and daily inspections to ensure the air convection vents are not blocked (per the requirements of the approved design bases). The program also includes provisions where modifications may be appropriate.

Table 6-3 Example aging management program for Reinforced Concrete Structures

Element	Description
1. Scope of Program	The scope of the program includes the following aging management activities: 1. visual inspection of above-grade (readily accessible, normally inaccessible) and below-grade (underground) concrete areas (see Element 4 for sample size and justification of areas to be inspected) 2. groundwater chemistry monitoring program to identify conditions conducive to the following below-grade (underground) aging mechanisms: • corrosion of embedded steel • chemical attack (chloride- and sulfate-induced degradation) 3. radiation surveys[1] to: • ensure compliance with 10 CFR 72.104 (i.e., dose equivalent requirements beyond the controlled area during normal and off-normal conditions of storage) • monitor performance of the concrete as a neutron/gamma shield at near-system locations as an indicator of concrete degradation The program provides means to adequately identify the following aging effects, as described in ACI 349.3R-02 (ACI, 2010) and SEI/ASCE 11-99 (SEI/ASCE, 2000): • cracking or loss of material (spalling, scaling) due to Freeze and thaw degradation • cracking, loss of material (spalling, scaling), loss of strength and reduction of concrete pH (corrosion resistance of steel reinforcement) due to aggressive chemical attack • cracking and loss of strength due to reaction with aggregates • cracking, loss of material, and loss of strength due to corrosion of embedded steel • increase in porosity/permeability, loss of strength, and reduction in concrete pH due to leaching of calcium hydroxide • cracking due to differential settlement • loss of material (spalling, scaling) due to salt scaling • loss of material (spalling, scaling), loss of strength, increased porosity and permeability, and reduction in concrete pH

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[1] The NRC reviewer should consider the design features of the DSS when determining if radiation surveys can be excluded from the scope of this AMP on a case-by-case basis. For example, internal surfaces of a concrete overpack may be permanently blocked by a steel liner, which may prevent assessing the condition of those concrete surfaces by remote visual inspection. The NRC reviewer should evaluate any engineering justification and/or operating experience to determine if visual inspections of readily accessible and normally inaccessible (i.e., not permanently blocked) surfaces can adequately characterize the condition of the structure and provide reasonable assurance that the intended functions are maintained during the period of extended operation.

Table 6-3 Example aging management program for Reinforced Concrete Structures	
Element	**Description**
	(corrosion resistance of steel reinforcement) due to microbioligical degradation Additional site-specific AMPs may be required for the following scenarios: • A dewatering system is used to prevent long-term settlement. • The design bases include embedded aluminum subcomponents without a protective insulating coating. • Protective coatings are relied upon to manage the effects of aging for a subcomponent.
2. Preventive Actions	Preventive actions include continuance of inspections to ensure that air inlet/outlet vents are not blocked and/or temperature monitoring, if applicable, to ensure design temperature limits are not exceeded (see Section 6.8, AMP on Ventilation Systems). These inspections would be part of the approved design bases and be continued for the sample size and inspection frequency identified in the respective technical specification (TS). Additional preventive actions are not required for structures designed and fabricated in accordance with ACI 318 (ACI, 2011) or ACI 349 (ACI, 2007a), as specified in the design bases. Otherwise, a site-specific AMP may be required.
3. Parameters Monitored or Inspected	For visual inspections, the parameters monitored or inspected quantify the following aging effects: • cracking • loss of material (spalling, scaling) • loss of bond • increased porosity/permeability AMP procedures reference the following parameters for characterizing the above aging effects, as appropriate, per the acceptance criteria:[2] • affected surface area • geometry/depth of defect • cracking, crazing, delaminations, drummy areas • curling, settlements or deflections • honeycombing, bug holes • popouts and voids • exposure of embedded steel • staining/ evidence of corrosion

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[2] The terminology is consistent with ACI standard CT-13 (ACI, 2013b).

Table 6-3 Example aging management program for Reinforced Concrete Structures

Element	Description
	• dusting, efflorescence of any color The parameters evaluated consider any surface geometries that may support water ponding and potentially increase the rate of degradation. For the groundwater chemistry program, the parameters monitored or inspected include: • water pH • concentration of chlorides and sulfates in the water For radiation surveys, the parameters monitored or inspected include gamma dose rate and neutron fluence rate.
4. Detection of Aging Effects	<u>Method or technique</u> Visual inspections of readily accessible areas are performed with feeler gauges, crack comparators, or other suitable visual quantification methods per the acceptance criteria in ACI 349.3R-02 (ACI, 2010). Visual inspections of normally inaccessible areas are performed using a remote inspection system that has been qualified for the specific DSS and site-specific characteristics. Procedures for remote visual inspections should be demonstrated to ensure the acceptance criteria in ACI 349.3R-02 (ACI, 2010) are achievable; procedure attributes should include, for example, equipment resolution and lighting requirements and should reference applicable standards when possible. Groundwater chemistry is characterized using a chemical analysis method with a valid measurement range and adequate resolution and sensitivity. Procedures for groundwater chemistry analyses should be demonstrated to ensure the acceptance criteria in ASME Code Section XI, Subsection IWL, are achievable Radiation surveys are performed using calibrated neutron and gamma detectors with valid energy ranges, per the acceptance criteria (see Element 6). Procedure attributes for all inspection and monitoring activities within the scope of this program should be commensurate with 10 CFR 72.164 and 10 CFR Part 50, Appendix B, as appropriate.

Table 6-3 Example aging management program for Reinforced Concrete Structures	
Element	**Description**
	Frequency of Inspection The schedule for visual inspections is commensurate with ACI 349.3R-02 (ACI, 2010). Alternative inspection frequencies must be adequately justified by a valid technical basis (engineering justification, operational experience data). Inspections of above-grade (both readily accessible and normally inaccessible) areas are conducted at least once every 5 years. The inspections of below-grade (underground) areas are opportunistic; inspections are performed when excavations occur for any reason. The frequency for monitoring groundwater chemistry is justified (e.g., quarterly, semiannually), per an adequate technical basis (site-specific operating experience, engineering justification). The frequency for radiation surveys is justified (e.g., quarterly), per an adequate technical basis (engineering justification, operating experience). Sample size Visual inspections cover 100 percent of readily accessible surfaces (or a justified coverage) of all concrete structures within the scope of renewal (e.g., all normally accessible exterior surfaces of all loaded overpacks), and 100 percent of normally inaccessible surfaces (or a justified coverage) for a justified subset of the reinforced concrete structures within the scope of renewal (e.g., interior surfaces of two overpacks, including the overpack earliest loaded and the overpack loaded with the highest heat-load canister). The extent of inspection coverage should be specified and demonstrated to sufficiently characterize the condition of the structure. For the groundwater chemistry program and radiation surveys, the sample size identifies and justifies specific locations where inspection or monitoring will be conducted to sufficiently characterize the condition of the structure (e.g., periodic dose rate measurements will be performed at the same locations specified in the TS for dose rate measurements at loading). Data collection: Data collection for visual inspections is commensurate with consensus standards and guides (see ACI 224.1R (ACI, 2007b) for quantitative analysis (crack width, extent), ACI 562, (ACI, 2013a), ACI 364.1R (ACI, 2007c)).

Table 6-3 Example aging management program for Reinforced Concrete Structures	
Element	**Description**
	Data from all inspection and monitoring activities, including evidence of degradation and its extent and location, shall be documented on a checklist or inspection form. The results of the inspection shall be documented, including descriptions of observed aging effects and supporting sketches, photographs, or video. Corrective actions from AMP activities shall also be documented. An adequate clearinghouse is used for documenting inspection and monitoring operating experience. <u>Timing</u> Initial inspections and monitoring activities are completed before entering the period of extended operation; the activities may be part of a preapplication inspection or a general-licensee baseline inspection (see NUREG–1927, Rev. 1 (NRC, 2016)).
5. Monitoring and Trending	Monitoring and trending methods are commensurate with concensus defect evaluation guides and standards (see ACI 201.1R (ACI, 2008a), ACI 207.3R (ACI, 2008b), ACI 364.1R (ACI, 2007c), ACI 562 (ACI, 2013a), or ACI 224.1R (ACI, 2007b) for crack evaluation). Inspection and monitoring results are compared to those obtained during previous inspections, so that the progression of degradation can be evaluated and predicted. Monitoring and trending methods reference plans and procedures used to: • establish a baseline before or at the beginning of the period of extended operation • track trending of parameters or effects not corrected in a previous inspection, for example — crack growth/extent — pore/void density and affected areas — dose rates
6. Acceptance Criteria	The acceptance criteria for visual inspections are commensurate with the 3-tier quantitative criteria in ACI 349.3R-02: • Tier 1: acceptance without further evaluation • Tier 2: acceptance after review • Tier 3: acceptance requiring further evaluation All conditions not meeting the Tier 2 acceptance criteria are evaluated in the Corrective Action Program (CAP) to reasonably

Table 6-3 Example aging management program for Reinforced Concrete Structures	
Element	**Description**
	ensure that the intended functions of the structure will be adequately maintained until a followup inspection, at a minimum. The acceptance criteria for the groundwater chemistry program are commensurate with ASME Code Section XI, Subsection IWL, which states that an aggressive below-grade environment is defined as pH < 5.5, chlorides > 500 ppm, or sulfates > 1500 ppm. The acceptance criteria for radiation surveys are justified and sufficient to ensure compliance with 10 CFR 72.104 and identify dose rates that statistically exceed calculated or expected dose rates at predetermined measurement locations. The adequacy of the acceptance criteria considers measured dose rates versus calculated or expected dose rates for a DSS, given the DSS contents and accounting for the decay of the source term since the DSS loading. Measurement locations should be consistent with those specified in the license or Certificate of Compliance (CoC) conditions or TS (if any) and locations where dose rates were calculated in the final safety analysis report (FSAR) and likely measured at the time of loading. Alternative acceptance criteria should be reviewed on a case-by-case basis. For such cases, the acceptance criteria shall: • include a quantitative basis (justifiable by operating experience, engineering analysis, consensus codes and standards) • avoid use of nonquantifiable phrases (e.g., significant, moderate, minor, little, slight, few) • be achievable and clearly actionable
7. Corrective Actions	Results that do not meet the acceptance criteria are addressed as conditions adverse to quality or significant conditions adverse to quality under those specific portions of the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that corrective actions are completed within the specific- or general-licensee's Corrective Action Program (CAP), and include provisions to • perform functionality assessments • perform apparent cause evaluations, and root cause evaluations • address the extent of condition • determine actions to prevent recurrence for significant conditions adverse to quality; ensure justifications for nonrepairs

Table 6-3 Example aging management program for Reinforced Concrete Structures	
Element	**Description**
	- trend conditions - identify operating experience actions, including modifications to the existing AMP (e.g., increased frequency) - determine if the condition is reportable to the NRC per 10 CFR 72.75 Corrective actions shall be consistent with applicable consensus rehabilitation guides or standards, unless an engineering justification is provided (e.g., for cracking: ACI 224.1R, ACI 562, ACI 364.1R, and ACI RAP Bulletins; for spalling/scaling: ACI 562, ACI 364.1R, ACI 506R, and ACI RAP Bulletins).
8. Confirmation Process	The confirmation process is commensurate with the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality. The confirmation process describes or references procedures to: - determine followup actions to verify effective implementation of corrective actions - monitor for adverse trends due to recurring or repetitive findings or observations.
9. Administrative Controls	The administrative controls are in accordance with the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the administrative controls include provisions that define: - instrument calibration and maintenance - inspector requirements (commensurate with ACI 349.3R-02) - record retention requirements - document control The administrative controls describe or reference: - methods for reporting results to the NRC per 10 CFR 72.75 - frequency for updating the AMP based on industrywide operational experience
10. Operating Experience	Structures monitoring programs using the acceptance criteria in ACI 349.3R-02 (ACI, 2010) have proven effective for aging management of concrete structures in nuclear power plants during their period of extended operation (NRC, 2010b). NUREG–1522 documents the results of a survey sponsored in 1992 by the Office of Nuclear Reactor Regulation to obtain information on the types of distress in the concrete and steel structures and components, the

Table 6-3 Example aging management program for Reinforced Concrete Structures	
Element	**Description**
	type of repairs performed, and the durability of the repairs. Licensees who responded to the survey reported cracking, scaling, and leaching of concrete structures. The degradation was attributed to drying shrinkage, Freeze and thaw, and abrasion. The NUREG also describes the results of NRC staff inspections at six plants. The staff observed concrete degradation, corrosion of component support members and anchor bolts, cracks and other deterioration of masonry walls, and groundwater leakage and seepage into underground structures. The observed and reported degradations were more severe at coastal plants than those observed in inland plants, as a result of brackish and sea water. Previous reactor license renewal applicants reported similar degradation and corrective actions taken through their structures monitoring program. NRC Information Notice 2011-20 (NRC, 2011) documents the occurrence of alkali-silica reaction (ASR)-induced concrete degradation of a seismic Category 1 below-grade structure at the Seabrook Station power plant. The concrete used in the structure passed all industry standard ASR screening tests (ASTM, 2007, 2012) at the time of construction; however, ASR-induced degradation was identified in August 2010. The licensee completed a prompt operability determination that concluded margins to the design limits remained such that the structural integrity of the building continued to be demonstrated. NRC Information Notice 2013-07 documents the occurrence of Freeze and thaw cracking near the anchor blockout holes on the roof of horizontal storage modules (HSMs) at an ISFSI in Idaho. The cracking led to water migration into the concrete, resulting in efflorescence of calcium carbonate deposits. The degradation of the roofslabs was not related to age-related degradation but to a design feature leading to water accumulation. More extensive visual inspections of the HSMs also revealed map cracking on the vertical wall surfaces, random and radial cracking at the door edges in base units, and spalling at the bottom edge of shield walls. The licensee conducted nondestructive and destructive examination, which revealed adequate concrete quality and compressive strength. Additional visual inspections of concrete structures in DSSs have been conducted at the Calvert Cliffs ISFSI (Gellrich, 2012) and the Palisades ISFSI. Remote visual inspections of two HSMs at the Calvert Cliffs ISFSI revealed efflorescence of the concrete and the formation of calcium carbonate stalactites in the 2-inch gap between the heat shield and the concrete ceiling. These stalactites were attributed to water ingress through the outlet vent stack. A condition report was issued that did not identify an operability issue.

Table 6-3 Example aging management program for Reinforced Concrete Structures

Element	Description
	Inspections of the exterior surfaces of a ventilated concrete cask (VCC) and the concrete support pad at the Palisades ISFSI revealed bugholes exceeding preestablished acceptance criteria and requiring grout repair, and a void at the interface between the VCC bottom plate and the vertical VCC concrete wall. No conditions were identified to compromise the intended functions of the VCC. Walkdowns and visual inspections of readily accesible surfaces of concrete overpacks and HSMs are generally conducted during the initial storage period, although the acceptance criteria may vary from those in ACI 349.3R.02 (ACI, 2010). The NRC reviewer should evaluate relevant inspection results included in the renewal application, based on design and environmental similarities, and evaluate if activities in this generic AMP should be augmented as a result of those inspections.
References	ACI. ACI 506R-05, “Guide to Shortcrete.” American Concrete Institute. 2005. _____. ACI 349-06, “Code Requirements for Nuclear Safety-Related Concrete Structures.” American Concrete Institute. 2007a. _____. ACI 224.1R-07, “Causes, Evaluation, and Repair of Cracks in Concrete Structures.” American Concrete Institute. 2007b. _____. ACI 364.1R-07, “Guide for Evaluation of Concrete Structures before Rehabilitation.” American Concrete Institute. 2007c. _____. ACI 201.1R-08, “Guide for Conducting a Visual Inspection of Concrete in Service.” American Concrete Institute. 2008a. _____. ACI 207.3R-94, “Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions.” American Concrete Institute. 2008b. _____. ACI 349.3R-02, “Evaluation of Existing Nuclear Safety-Related Concrete Structures.” American Concrete Institute. 2010. _____. ACI 318-11, “Building Code Requirements for Structural Concrete.” American Concrete Institute. 2011. _____. ACI 562-13, “Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings.” American Concrete Institute. 2013a. _____. ACI CT-13, “ACI Concrete Terminology.” American Concrete Institute. 2013b.

Table 6-3 Example aging management program for Reinforced Concrete Structures	
Element	**Description**
	ASME Boiler and Pressure Vessel Code, Section XI, Subsection IWL (2013), “Requirements for Class CC Concrete Components of Light-Water-Cooled Plants” ASTM International. ASTM C289, “Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method).” West Conshohocken, Pennsylvania: American Society for Testing and Materials. 2007. _____. ASTM C295, “Standard Guide for Petrographic Examination of Aggregates for Concrete.” West Conshohocken, Pennsylvania: American Society for Testing and Materials. 2012. Gellrich, G. “Calvert Cliffs Nuclear Power Plant.” Letter to U.S. Nuclear Regulatory Commission, Response to Request for Supplemental Information. RE: Calvert Cliffs Independent Spent Fuel Storage Installation License Renewal Application (TAC No. L24475). ADAMS Accession No. ML12212A216. 2012. NRC. “Standard Review Plan for Spent Fuel Dry Storage Facilities.” NUREG–1567, Rev. 0. Washington, DC. ADAMS Accession No. ML003686776. 2000. _____. “Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility.” NUREG–1536, Rev. 1. ADAMS Accession No. ML091060180.Washington, DC. 2010a. _____. NUREG–1801, “Generic Aging Lessons Learned (GALL) Report.” Rev. 2, Washington DC. ADAMS Accession No. ML103490041. 2010b. _____. “Information Notice 2011-20, Concrete Degradation by Alkali-Silica Reaction.” Washington, DC: U.S. Nuclear Regulatory Commission. ADAMS Accession No. ML112241029. 2011. _____. NUREG–1927, “Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel.” Revision 1. Washington, DC: U.S. Nuclear Regulatory Commission. ADAMS Accession No. ML16179A148. 2016. SEI/ASCE 11-99, “Guideline for Structural Condition Assessment of Existing Buildings.” 2000.

6.7 External Surfaces Monitoring Of Metallic Components

An example AMP for external surfaces monitoring of metallic components is provided below. The AMP manages all metallic surfaces that are directly exposed to outdoor air, concrete, or are sheltered within DSS overpacks, except for stainless steel storage canisters and transfer casks, which are addressed by other AMPs. The AMP is a condition monitoring program that consists of periodic visual inspections to monitor for corrosion, wear, cracking, and loss of preload (bolting).

Table 6-4 Example aging management program for External Surfaces Monitoring Of Metallic Components

Element	Description
1. Scope of Program	This program manages the effects of aging for the external surfaces of steel and stainless steel components that are directly exposed to outdoor air or are sheltered within DSS overpacks (e.g., NUHOMS HSM, HI-STORM). The scope of the program includes metallic overpack exterior surfaces, dry storage canister support structures, access doors, vents, heat shields, embedments and anchorages, bolting, and other components important to safety. The scope of this program does not include stainless steel dry storage canisters housed within overpacks, transfer casks, or the top closure (confinement) boundary of bolted casks. The Localized Corrosion and Stress corrosion Cracking of Welded Stainless Steel Dry Storage Canisters AMP manages the effects of aging for stainless steel canisters. The Transfer Casks AMP manages the effects of aging of all transfer cask components. The Bolted Cask Seal Leakage Monitoring AMP manages the effects of aging on the integrity of the top confinement boundary of bolted spent fuel storage casks. Periodic visual inspections monitor for general and localized corrosion, wear, cracking, and loss of preload (bolting).
2. Preventive Actions	This program is a condition monitoring program to detect evidence of degradation. It does not provide guidance for the prevention of aging.
3. Parameters Monitored/ Inspected	This program monitors the condition of external metallic surfaces to identify general corrosion, localized corrosion, wear, and loss of preload of bolted connections. Localized corrosion of stainless steels may be a precursor to SCC. Parameters monitored or inspected for external metallic surfaces include: • visual evidence of discontinuities, imperfections, and rust staining indicative of corrosion, SCC, and wear • visual evidence of loose or missing bolts, physical displacement, and other conditions indicative of loss of preload • visual evidence of coating degradation (e.g., blisters, cracking, flaking, delamination) indicative of corrosion of the base metal
4. Detection of Aging Effects	<u>Readily Accessible Surfaces</u> Visual inspections are performed in accordance with ASME Code Section XI, Article IWA-2213, for VT-3 examinations. The inspections cover 100 percent of normally accessible surfaces, including the external surfaces of metallic overpacks, bolting, lightning protection system components, access doors, vents, and other metallic components.

Table 6-4 Example aging management program for External Surfaces Monitoring Of Metallic Components	
Element	**Description**
	<u>Normally Inaccessible Surfaces</u> Opportunistic visual inspections are performed with remote inspection techniques on metallic surfaces within overpacks that are accessed during inspections of dry storage canisters, including heat shields, canister support structures, and other metallic components. The condition of metallic surfaces in contact with concrete (i.e., overpack/cask bottoms) are assessed with visual inspections on a justified frequency. Procedures for visual inspections should be demonstrated; procedure attributes should include, for example, equipment resolution and lighting requirements and should reference applicable standards (e.g., ASTM Code Section XI, Article IWA-2200, for VT-3 examinations). The extent of inspection coverage should be specified and demonstrated to sufficiently characterize the condition of the metallic components. <u>Sample Size</u> The readily accessible exterior metallic surfaces of all casks and overpacks are inspected. The inspections of normally inaccessible surfaces within overpacks is opportunistic; inspections are performed whenever the overpacks are accessed for dry storage canister inspections. Overpack and cask bottoms are inspected on a justified sample size. <u>Frequency</u> Inspections of readily accessible surfaces are conducted at least once every 5 years. Normally inaccessible surfaces within overpacks are inspected when those surfaces are accessed during remote inspections of dry storage canisters. Overpack and cask bottoms are inspected on a justified frequency. <u>Data Collection</u> Data from the examination, including evidence of degradation and its extent and location, shall be documented on a checklist or inspection form. The results of the inspection shall be documented, including descriptions of observed aging effects and supporting sketches, photographs, or video. Corrective actions resulting from each AMP inspection shall also be documented. <u>Timing</u> Initial inspections are completed before entering the period of extended operation.

Table 6-4 Example aging management program for External Surfaces Monitoring Of Metallic Components

Element	Description
5. Monitoring and Trending	Inspection results are compared to those obtained during previous inspections, so that the progression of degradation can be evaluated and predicted. Monitoring and trending methods reference plans and procedures used to: • establish a baseline before or at the beginning of the period of extended operation • track trending of parameters or effects not corrected following a previous inspection, including — locations and size of any areas of corrosion, wear, or cracking — disposition of components with identified aging effects and the results of supplemental inspections
6. Acceptance Criteria	The acceptance criteria for the visual inspections are: • no detectable loss of material from the base metal, including uniform wall thinning, localized corrosion pits, and crevice corrosion • no red-orange-colored corrosion products on the base metal, coatings, or concrete • no coating defects (e.g., blisters, cracking, flaking, delamination) • no indications of loose bolts or hardware, displaced parts If evidence of corrosion, wear, or coating degradation is identified, then the severity of the degradation must be determined using approved site-specific procedures. These may include additional visual, surface or volumetric nondestructive examination (NDE) methods to determine the loss of material and, for welded stainless steels, the presence of cracking. Alternative acceptance criteria are developed from system-specific design standards, industry codes or standards, or engineering evaluation. Where possible, acceptance criteria are quantitative (e.g., minimum wall thickness). Where qualitative acceptance criteria are used, the criteria are sufficiently clear to reasonably ensure that a singular decision is derived based on the observed condition, avoiding the use of ambiguous phrases (e.g., significant, moderate). EPRI technical reports, Technical Report (TR)-1007933, “Aging Assessment Field Guide” (EPRI, 2003), and TR-1009743, “Aging Identification and Assessment Checklist: Mechanical Components” (EPRI, 2004), provide general guidance for the evaluation of materials and the development of criteria for their acceptance when performing visual inspections.

Table 6-4 Example aging management program for External Surfaces Monitoring Of Metallic Components	
Element	**Description**
7. Corrective Actions	Results that do not meet the acceptance criteria are addressed as conditions adverse to quality or significant conditions adverse to quality under those specific portions of the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that corrective actions are completed within the specific- or general-licensee's Corrective Action Program (CAP), and include provisions to • perform functionality assessments • perform apparent cause evaluations and root cause evaluations • address the extent of condition • determine actions to prevent recurrence for significant conditions adverse to quality; ensure justifications for nonrepairs • trend conditions • identify operating experience actions, including modification to the existing AMP (e.g., increased frequency) • determine if the condition is reportable to the NRC per 10 CFR 72.75
8. Confirmation Process	The confirmation process is commensurate with the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality. The confirmation process describes or references procedures to: • determine followup actions to verify effective implementation of corrective actions • monitor for adverse trends due to recurring or repetitive findings or observations.
9. Administrative Controls	The administrative controls are addressed through those portions of the specific- or general-licensee QA program that are used to meet 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B.
10. Operating Experience	External surface inspections through system inspections and walkdowns in support of the Maintenance Rule (10 CFR Part 50.65) have proven effective in maintaining the material condition of nuclear power plant systems. NRC Information Notice 2012-20 (NRC, 2012) documents cases of atmospheric CISCC of welded stainless steel piping systems and tanks at operating reactor locations. Atmospheric CISCC growth rates determined from operational experience at both domestic and foreign nuclear power plants, include events at San Onofre, Turkey Point,

Table 6-4 Example aging management program for External Surfaces Monitoring Of Metallic Components

Element	Description
	St. Lucie, and Koeberg (South Africa), range from 3.6×10^{-12} to 2.9×10^{-11} m/sec for components at ambient temperatures.
References	EPRI. EPRI Technical Report 1007933, “Aging Assessment Field Guide.” Palo Alto, California: Electric Power Research Institute. December 2003. _____. EPRI Technical Report 1009743, “Aging Identification and Assessment Checklist–Mechanical Components.” Palo Alto, California: Electric Power Research Institute. August 27, 2004. NRC. NRC Information Notice 2012-20, “Potential Chloride-Induced Stress Corrosion Cracking of Austenitic Stainless Steel and Maintenance of Dry Cask Storage System Containers.” Washington, DC: U.S. Nuclear Regulatory Commission. November 14, 2012.

6.8 Ventilation Systems

An example AMP for ventilation systems is provided below. The AMP manages all inlet and outlet vents and conduits providing convective cooling in DSSs. This is a condition monitoring program that performs periodic visual inspection of vents as defined in the approved design bases, with additional focused inspections to address normally unobservable vent areas, as well as evidence of degradation that could result in obstructions. Temperature monitoring may be used in lieu of the periodic visual surveillances to verify cooling performance.

Table 6-5 Example aging management program for Ventilation Systems

Element	Description
1. Scope of Program	This program manages potential loss of cooling capabilities due to blockage of the ventilation system (air inlet/outlets, convection conduits) in DSSs. Surveillance/monitoring and focused inspections of the ventilation system (i) ensure that blockage does not result in design temperature limits being exceeded and (ii) prevent unanticipated adverse degradation of components of the DSS (e.g., high-temperature dehydration of the concrete[1], hydride reorientation due to fuel cladding temperatures exceeding design-bases limits[2]). <u>Visual Surveillances of Inlet and Outlet Vents</u> The scope of the program includes continuance of surveillances (periodic walkdowns) of air inlet/outlet vents, as defined in the approved design bases (FSAR, license/CoC TS). The program provides for additional focused inspections if (i) the normally unobservable vent area exceeds the allowable blockage, and (ii) there is evidence of degradation of other components (e.g., loss of coatings, spalling or leaching of the concrete overpack) that could result in obstructions.[3] <u>Temperature Monitoring</u> The scope of the program includes temperature monitoring of DSS components in lieu of visual surveillances, as specified in the approved design bases (FSAR, license/CoC TS). Continuance of temperature monitoring provides a means to detect anomalous temperature changes in the DSS. The program further provides for focused visual inspections of the ventilation system (inlet/outlet vents, conduits) in the event that anomalous temperature changes are measured. Focused visual inspections allow for detection of degradation of other components that could result in obstructions (e.g., loss of coatings, inner spalling or leaching of the concrete overpack). The scope of the program does not include inspection and/or maintenance activities for aging of bird screens used to prevent vent blockage (see the External Surfaces Monitoring of Metallic Components AMP).

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[1] See NUREG–1536/NUREG–1567 (NRC, 2010, 2002) for design criteria on maximum concrete temperatures.

[2] See ISG-11, Revision 3 (NRC, 2003), for cladding considerations for the transportation and storage of spent fuel.

[3] The approved design bases have adequately addressed the occurrence of extreme natural phenomena, such as heavy snowstorm or flooding. The QA program ensures that corrective actions are completed within the specific- or general-licensee's CAP in the event of extreme natural phenomena.

Table 6-5 Example aging management program for Ventilation Systems	
Element	**Description**
2. Preventive Actions	This program is a condition monitoring program to detect obstruction or blockages of the ventilation system that could result in design-bases temperature limits being exceeded. It does not provide guidance for the prevention of aging of components.
3. Parameters Monitored/ Inspected	<u>Visual Surveillances of Inlet and Outlet Vents</u> Parameters monitored or inspected include blockage or obstruction in the air inlet and outlet vents. <u>Temperature Monitoring</u> Parameters monitored or inspected include temperature measurements of the DSS, which could be based on (i) direct measurements of the overpack temperatures, (ii) direct measurement of the canister temperatures, (iii) a comparison of the inlet and outlet temperature difference to predicted temperature differences for each individual overpack, or (iv) other means that would identify and allow for the correction of off-normal thermal conditions that could lead to exceeding design-bases temperature limits for the concrete and/or fuel cladding. <u>Focused Inspections</u> Parameters monitored or inspected include (i) blockage or obstructions of the air inlets/outlets and (ii) degradation of other components (e.g., loss of coatings, inner spalling or leaching of the concrete overpack) that could result in obstructions of inaccessible convective conduits.
4. Detection of Aging Effects	<u>Method/Technique</u> Visual surveillances of the air inlet/outlet vents are performed during periodic walkdowns, without the need of remote equipment. Surveilling personnel should have an unobstructed view of vent areas that allows confirmation that the maximum allowable blockage is not exceeded (up to the boundary of the vent bird screen, at a minimum). The maximum allowable blockage is defined in the approved design bases (FSAR, license/CoC TS). Temperature monitoring is performed with qualified and calibrated measurement devices or sensors that are maintained in accordance with the site QA program. Focused inspections are performed with remote inspection techniques. Procedures for remote visual inspections should be demonstrated; procedure attributes should include, for example, equipment resolution and lighting requirements, in consideration of the ventilation system design.

Table 6-5 Example aging management program for Ventilation Systems	
Element	**Description**
	<u>Frequency of Inspection/Monitoring</u> Visual surveillances and temperature monitoring are conducted at a frequency consistent with the approved design bases (i.e., as defined in the FSAR, or the relevant license/CoC TS). Generally, visual surveillances are conducted daily (not exceeding a 48-hour interval) and temperature monitoring is performed continuously. The frequency of focused inspections for vent areas should be justified based on the design (percentage of normally unobservable vent area relative to allowable blockage) and operable degradation modes of the storage system components that could lead to blockage. The frequency of focused inspections provides reasonable assurance that blockages in the normally inaccessible convective conduits will be identified before a loss of function by considering conduit-free volume relative to postulated obstructions (e.g., upon consideration of potential coating loss or concrete spalling relative to conduit-free volume). Previous operating experience may be used to justify the use of opportunistic inspections. When continuous temperature monitoring is used to verify ventilation performance, focused inspections are performed whenever anomalous temperatures are measured. <u>Sample Size</u> Visual surveillances include all directly observable areas of the inlet and outlet vents. Visual surveillances are performed on all loaded systems, or as justified by the approved design bases (i.e., as defined in the FSAR, or the relevant license/CoC TS). Temperature monitoring is performed in all loaded systems, or as justified by the approved design bases (i.e., as defined in the FSAR, or the relevant license/CoC TS). For focused inspections, the extent of inspection coverage should be specified and demonstrated to sufficiently characterize the condition of the ventilation system. Focused inspections include all normally unobservable vent areas exceeding the allowable blockage. The extent of inaccessible conduit inspection is justified based on the ventilation system design (conduit-free volume, accessibility) and consideration of operable degradation modes of the storage system materials. The use of continuous temperature monitoring may be used in lieu of focused inspections if anomalous temperatures are not measured. <u>Data Collection</u> Data collection should be consistent with site procedures in compliance with the specific- or general-licensee’s QA program.

Table 6-5 Example aging management program for Ventilation Systems	
Element	**Description**
	Timing A baseline focused inspection is conducted on a sample DSS upon entering the period of extended operation to identify any operable degradation modes that may result in an obstruction or blockage difficult to observe during a visual surveillance. The baseline-focused inspection includes 100 percent of the vents and inaccessible convective conduits of the sample DSS, or a justified volume based on design considerations (e.g., accessibility, dose rates). A baseline-focused inspection on a sample system is not necessary if temperature monitoring is used in lieu of visual surveillances.
5. Monitoring and Trending	Results from visual surveillances and temperature monitoring are trended to identify conditions (materials/environmental) leading to obstructions or blockages. Results from focused inspections are compared with prior inspections to monitor and trend operable degradation modes of the storage system materials that have resulted in partial blockage.
6. Acceptance Criteria	The acceptance criteria are defined to ensure that the need for corrective actions will be identified before (i) blockage results in design temperature limits being exceeded and (ii) unanticipated adverse degradation of components of the DSS results in a loss of intended function. Where possible, acceptance criteria are quantitative (e.g., 50-percent areal blockage or a specific allowed temperature range). Where qualitative acceptance criteria are used, the criteria are sufficiently clear to reasonably ensure that a singular decision is derived based on the observed condition, avoiding the use of ambiguous phrases (e.g., significant, moderate). The acceptance criteria for visual surveillances and focused inspections are justified based on the ventilation system design, thermal performance criteria, and consideration of operable degradation modes of the storage system materials. The acceptance criteria may be further justified by parallel maintenance activities under a separate AMP. The acceptance criteria for temperature monitoring are justified and conservative to the short-term temperature limits for a blocked vent condition, as defined in the approved design bases (i.e., as defined in the FSAR, or the relevant license/CoC TS).
7. Corrective Actions	Results that do not meet the acceptance criteria are addressed as conditions adverse to quality or significant conditions adverse to quality under those specific portions of the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or

Table 6-5 Example aging management program for Ventilation Systems	
Element	**Description**
	10 CFR Part 50, Appendix B, respectively. The QA program ensures that corrective actions are completed within the specific- or general-licensee's Corrective Action Program (CAP), and include provisions to: • perform functionality assessments • perform apparent cause evaluations and root cause evaluations • address the extent of condition • determine actions to prevent recurrence for significant conditions adverse to quality; ensure justifications for nonrepairs • trend conditions • identify operating experience actions, including modification to the existing AMP (e.g., increased frequency) • determine if the condition is reportable to the NRC per 10 CFR 72.75
8. Confirmation Process	The confirmation process is commensurate with the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality. The confirmation process describes or references procedures to: • determine followup actions to verify effective implementation of corrective actions • monitor for adverse trends due to recurring or repetitive findings or observations.
9. Administrative Controls	The administrative controls are addressed through those portions of the specific- or general-licensee QA program that are used to meet 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B. To ensure the temperature monitoring devices will remain accurate during the period of extended operation, the electronic circuitry associated with the temperature monitoring devices should be periodically calibrated in accordance with the licensee's QA requirement in 10 CFR 72.164 and specific-license requirement in 10 CFR 72.44(c)(3)(ii). In addition, the calibration data are periodically evaluated to identify anomalous trends that could indicate degraded instrumentation or degradation in the ventilation system. All external components in the temperature measurement devices should be periodically inspected and calibrated to ensure that no degradation due to corrosion, wear, or cracking has occurred.

Table 6-5 Example aging management program for Ventilation Systems	
Element	**Description**
10. Operating Experience	Visual surveillance of the exterior of the air inlets and outlets, inspections for ventilation blockage and temperature monitoring have been in effect at ISFSIs and have been proven effective in maintaining the convective cooling capabilities of DSSs during the initial license or certification period. Degradation of inner overpack materials has been observed in the field. NRC Information Notice 2013-07 (NRC, 2013) documents experience at the Three Mile Island, Unit 2, ISFSI, where water entered anchor bolt blockout holes on the roof of HSM concrete overpacks. Subsequent freeze and thaw cycles resulted in crack formation, crack growth, and efflorescence of the concrete. Inspections of two HSMs at the Calvert Cliffs ISFSI have also shown efflorescence of the concrete and the formation of calcium carbonate stalactites in the 2-inch gap between the heat shield and the concrete ceiling. These stalactites were observed near the outlet vent stack. A condition report was issued that did not identify an operability issue (CENG, 2012). Partial blockage of air inlet duct screens from snowfall has been identified. Decay heat from the spent fuel and/or stored heat in the overpack material (e.g., concrete) quickly melts any partial snow buildups after the snowfall has ceased. The existing activities (surveillance, monitoring, inspection) have proved adequate for natural phenomena during the initial license or certification period.
References	CENG. Letter to NRC, “Calvert Cliffs Nuclear Power Plant Independent Spent Fuel Storage Installation Material License No. SNM-2505, Docket No. 72-8, Response to Request for Supplemental Information, RE: Calvert Cliffs.” Independent Spent Fuel Storage Installation License Renewal Application, Calvert Cliffs Nuclear Power Plant, LLC. ADAMS Accession No. ML12212A216. July 27, 2012. NRC. NUREG–1567, “Standard Review Plan for Spent Fuel Dry Storage Facilities.” Washington DC: U.S. Nuclear Regulatory Commission. March 2000. _____. Interim Staff Guidance (ISG)–11, “Cladding Considerations for the Transportation and Storage of Spent Fuel.” Rev. 3. Washington DC: U.S. Nuclear Regulatory Commission. November 2003. _____. NUREG–1536, “Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility.” Washington DC: U.S. Nuclear Regulatory Commission. July 2010. _____. Information Notice 2013-11, “Premature Degradation of Spent Fuel Storage Cask Structures and Components from

Table 6-5 Example aging management program for Ventilation Systems	
Element	**Description**
	Environmental Moisture." Washington, DC: U.S. Nuclear Regulatory Commission. April 16, 2013.

6.9 Bolted Cask Seal Leakage Monitoring

This AMP manages the aging of all bolted casks that employ leakage monitoring to verify the integrity of the top confinement boundary. The program relies on existing pressure monitoring systems to assess the integrity of cask closure seals. The program also performs periodic visual inspections of normally inaccessible components under the cask protective cover to monitor for corrosion, coating degradation, loose bolts, and evidence of water intrusion.

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring

Element	Description
1. Scope of Program	This program is used to manage the aging effects on the integrity of the top confinement boundary of bolted spent fuel storage casks to ensure that timely and appropriate corrective actions can be taken to maintain the safe storage conditions of the casks. The aging effects include loss of material as a result of corrosion of the sealing surfaces, O-rings, and bolts; loss of strength due to thermal aging and change in dimension due to creep of the metallic O-rings that results in loss of sealing forces; and loss of preload of the closure bolts. The specific components and systems that are typically managed by this program include the shield lid, primary lid, closure lid, protective covers, O-ring assemblies, and associated bolts and welds. The types of bolted cask designs covered by the program include TN-24, -32, -40, and -68; NAC-S/T (I26), -C28 S/T, -I28 S/T, and -STC, CASTOR V/21 and X/33; and Westinghouse MC-10 bolted casks. The program relies on continuous pressure-leakage monitoring to verify the integrity of the confinement boundary. In addition, the program relies on periodic visual inspections for evidence of aging that may affect the intended function of the identified SSCs and subcomponents.
2. Preventive Actions	Preventive actions include compliance with the NRC's ISG on the materials selection for fabrication, design, and testing of casks, as described in NRC ISG-5, "Confinement Evaluation" (NRC, 1999); ISG-15, "Materials Evaluation" (NRC, 2001); and ISG-25, "Pressure and Helium Leakage Testing of the Confinement Boundary of Spent Fuel Dry Storage Systems" (NRC, 2010).
3. Parameters Monitored/ Inspected	The program relies on existing pressure-monitoring systems to assess the integrity of the cask closure seals. To verify the integrity of the seal assemblies in the bolted casks, these systems continuously monitor pressure: • between the metallic seal assemblies in the TN-24, -32, -40, and -68; NAC-S/T (I26), -C28 S/T, -I28 S/T, and -STC, CASTOR V/21 and X/33 casks, and • inside the cask cavity in the MC-10 casks. Parameters monitored/inspected for closure seal components include: • visual evidence of loss of material from general, localized, and galvanic corrosion • visual evidence of coating degradation that could indicate corrosion of the base metal

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring

Element	Description
	- visual evidence of clearances and physical displacements in bolted joints indicative of loss of preload or failed or missing components - visual evidence of water intrusion under the protective cover
4. Detection of Aging Effects	Aging effects may be revealed by: - overpressure and pressure loss (leakage) - water intrusion under protective covers - physical displacement, surface discontinuities, and imperfections indicative of loss of preload and corrosion. <u>Method or Technique</u> The program credits the pressure-monitoring system, which continuously monitors the pressure between the seal assemblies in the TN-24, -32, -40, and -68; NAC-S/T (I26), -C28 S/T, -I28 S/T, and -STC, CASTOR V/21 and X/33 metal casks and inside the cask cavity of the MC-10 casks. Continuous monitoring with a pressure alarm provides a means for early detection of aging effects on the seal assemblies. Direct or remote VT-3 visual examination, as described in ASME Code Section XI, Article IWA-2213 (ASME, 2007), shall be performed and evaluated by personnel qualified in accordance with the requirements of IWE-2330. <u>Frequency</u> Pressure-monitoring systems provide continuous monitoring of the bolted cask seal integrity. Checks of system operation shall be conducted, in accordance with the established requirements for these systems. Inspection and calibration of the components of the overpressure leakage-monitoring systems shall be performed in accordance with manufacturer specifications. Opportunistic inspections of the overpressure leakage monitoring systems shall be conducted when the protective cover plate is removed for other inspection or maintenance actions. Visual VT-3 inspection of the normally inaccessible top sealing components in the confinement boundary, after removing the protective cover, shall be conducted on a justified frequency. This includes the condition of externally accessible surfaces of the bolts, protective covers, and protective coatings. In addition, opportunistic inspections of the top confinement boundary subcomponents shall be conducted when the protective cover is removed for other inspection or maintenance actions.

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring

Element	Description
	Sample Size • pressure-monitoring system: all casks • visual inspection of normally inaccessible surfaces: as justified Data Collection Data from the examination, including the condition of the coating, locations and areas of coating degradation, and corrosion of any exposed steel surfaces shall be collected and documented on a checklist or visual inspection form. The results of the inspection shall be documented and include descriptions of observed aging effects and accompanied with sketches and/or photographs. Video coverage may also be used to document the inspection. Corrective actions resulting from each AMP inspection shall also be documented. Timing of Inspections Initial visual inspection of normally inaccessible surfaces and subcomponents shall be completed before entering the period of extended operation. Licensees may credit inspections conducted within the 5 years before the period of extended operation.
5. Monitoring and Trending	The pressure-monitoring data are trended to provide early detection of aging effects that result in leakage and to indicate when corrective action needs to be taken to maintain safe storage conditions. The results of visual inspections are documented, including evidence of corrosion of subcomponents, failure of protective coatings, and physical displacement of subcomponents of the cask-sealing system. Locations of all areas of degradation are documented to allow a direct comparison to prior inspection results. The inspection results will be documented and trended to identify aging-related degradation, the need for supplemental inspections, mitigation actions, and repair or replacement of subcomponents affected by aging. Corrective actions will be recorded and trended to evaluate the effectiveness of the actions taken.
6. Acceptance Criteria	Pressure readings should be within the range stated by the Certificate of Compliance (CoC) holder’s, general licensee’s, or site-specific licensee’s TS. Casks with pressure-monitoring systems in the alarmed condition do not meet the acceptance criteria. The CoC holder’s, general licensee’s, or site-specific licensee’s TS contain pressure-monitoring alarm response procedures that include criteria and specifications for corrective actions and response.

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring	
Element	**Description**
	For the cask-sealing subcomponents, the acceptance criteria for visual inspections are the absence of: • coating degradation, including blistering, peeling or flaking • visual indication of corrosion on steel surfaces normally protected by a coating • loose or missing hardware • displaced subcomponents or parts If coating degradation and corrosion are identified, then the severity of corrosion must be determined using approved site-specific or general licensee procedures. These may include additional visual, surface, or volumetric NDE methods to determine the loss of material. Corrosion that results in a loss of material that does not meet the design specifications is not acceptable for continued service and must be repaired or replaced.
7. Corrective Actions	Results that do not meet the acceptance criteria are addressed as conditions adverse to quality or significant conditions adverse to quality under those specific portions of the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that corrective actions are completed within the specific- or general-licensee's Corrective Action Program (CAP), and include provisions to: • perform functionality assessments • perform apparent cause evaluations and root cause evaluations • address the extent of condition • determine actions to prevent recurrence for significant conditions adverse to quality; ensure justifications for nonrepairs • trend conditions • identify operating experience actions, including modification to the existing AMP (e.g., increased frequency) • determine if the condition is reportable to the NRC per 10 CFR 72.75 Once the low-pressure alarm is triggered, troubleshooting of the pressure leakage should be performed and, if necessary, an engineering evaluation conducted to determine whether the degradation of the seal assemblies requires immediate correction.
8. Confirmation Process	The confirmation process is commensurate with the specific- or general-licensee QA program approved under 10 CFR Part 72,

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring

Element	Description
	Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality. The confirmation process describes or references procedures to: • determine followup actions to verify effective implementation of corrective actions • monitor for adverse trends due to recurring or repetitive findings or observations.
9. Administrative Controls	The pressure-leakage monitoring system is periodically checked to ensure the system is functioning properly. Maintenance, calibration, and replacement of pressure transducers are performed in accordance with manufacturer requirements. The administrative controls will be commensurate with the specific or general licensee QA program and consistent with 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B. The QA program ensures that inspections, evaluations, and corrective actions are completed in accordance with the specific or general licensee's CAP. The requirements of 10 CFR Part 72, Appendix G, and 10 CFR Part 50, Appendix B, are acceptable to address the corrective actions, confirmation process, and administrative controls.
10. Operating Experience	Existing Operational Experience Helium leakage in two of the TN-68 bolted casks at Peach Bottom was detected in October 2010 (NRC, 2013). The root cause analyses indicated that the leakage in one cask was caused by a material defect in the weld plug that provides sealing of the drilled inter-seal passageway associated with the drain port penetration of the cask lid. The defective welds were repaired in accordance with the ASME Code and cask design requirements. In the other cask, leakage existed in the cask main lid outer closure seal. The seal leakage was caused by galvanic corrosion at the interface between the aluminum-clad cask lid seal and the stainless steel clad cask body sealing surface of the outer portion of the cask lid seal. The corrosion resulted from water infiltration through the access plate in the protective cover. The primary corrective actions involved improving the access plate design and developing a method for verifying protective cover seal integrity. Additional corrective actions included a change to the torqueing process for the lid bolts and ensuring that the access plate gaskets and O-rings were inspected at installation. Corrosion of the TN-32 lid bolts and outer metallic lid seals has been observed in the Surry ISFSI owing to external water

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring

Element	Description
	intrusion near the lid bolts and outer metallic seals, resulting in five seal replacements. One seal on a CASTOR X/33 cask has also been replaced at Surry (Virginia Electric and Power Company, 2002). An inspection was carried out in 2011 on the lead cask TN-40 01 at Prairie Island in conjunction with the license renewal application for the ISFSI (Schimmel, 2012). The components inspected included the carbon steel cask bottom and underlying concrete pad; the cask shell, lid, lid bolts, and trunnions; and the top neutron shield enclosure and shield bolts. In addition, the cask protective cover was removed to permit visual inspection of the protective cover, bolts, and seal; the access cover and bolts; and the overpressure tank, isolation valve and tubing, port cover, and port cover bolts. The only significant degradation observed was disbondment of approximately 25 percent of the protective coating on the bottom of the cask, minor uniform general corrosion at the upper trunnions, and a very minor rust coating on the stainless steel portions of the containment flange. In addition, the protective cover was found to have thin uniform corrosion on the flange sealing surface on the outer side of the O-ring and minor corrosion at the cover bolt holes, and the cask access cover had minor rust spots on the outside at the bolt holes. The protective cover Viton O-ring was in good condition and was not replaced, and the access cover gasket was also in good condition but was replaced. The protective cover on TN-40 cask number 13 was also removed to permit a visual inspection. Here, all components were found to be in good condition, and the only degradation noted was minor rust stains on the protective coating directly below the access cover from corrosion products dripping off the access cover. An inspection of an MC-10 cask was performed after about 20 years in service at Surry (Virginia Electric and Power Company, 2006). Twelve knurled nuts, which fasten the closure cover to the cask, were removed for inspection. While there was some oxidation of the outer O-ring edge, the O-ring seal surface and the areas underneath the closure cover had no cracks or indications of degradation. Stress relaxation and leakage tests on Helicoflex metallic seals, which are used in the CASTOR and TN cask designs, have been conducted in Germany at temperatures from room temperature to 150 degrees C [302 degrees F]. These tests found that the pressure force on the seal and its elastic recovery (or usable resilience) decrease approximately linearly when plotted against the logarithm of time, but usable lives beyond 40 years with acceptable leak rates are extrapolated. Corrosion tests were also initiated on this same seal design in 2001 with borated (2,400 ppm) water or a NaCl solution (10^{-3} mol) between the inner and outer jackets of the seal, and no

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring	
Element	**Description**
	increase in leakage rate has been detected to date (Völzke et al., 2012; Völzke et al., 2013). In addition, the behavior of elastomer seals at low temperature (below room temperature) has been studied to determine the minimum temperature at which these materials can function in DSS applications (Wolff et al., 2013).
References	ASME. "Boiler and Pressure Vessel Code Section XI—Rules for Inservice Inspection of Nuclear Power Plant Components." New York, New York: American Society of Mechanical Engineers. 2007. Code of Federal Regulations. Title 10, Energy, Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste." Washington, DC: Office of the Federal Register. 2015a Code of Federal Regulations. Title 10, Energy, Part 50, "Domestic Licensing of Production and Utilization Facilities." Washington, DC: Office of the Federal Register. 2015b. NRC. "Confinement Evaluation." Interim Staff Guidance-5. Rev. 1. Washington, DC: U.S. Nuclear Regulatory Commission. 1999. _____. "Materials Evaluation. " Interim Staff Guidance-15. Rev. 1. Washington, DC: U.S Nuclear Regulatory Commission. 2001. _____. "Pressure and Helium Leakage Testing of the Confinement Boundary of Spent Fuel Dry Storage Systems." Interim Staff Guidance-25. Washington, DC: U.S. Nuclear Regulatory Commission. 2010. _____. "Premature Degradation of Spent Fuel Storage Cask Structures and Components from Environmental Moisture." Information Notice 2013-07. Washington, DC: U.S. Nuclear Regulatory Commission. 2013. Schimmel, M. "Prairie Island Independent Spent Fuel Storage Installation, Attachment 1 to Letter to U.S. Nuclear Regulatory Commission, Responses to Requests for Supplemental Information, RE: Prairie Island Independent Spent Fuel Storage Installation License Renewal Application." (TAC No. L24592). ADAMS Accession No. ML12065A073. 2012. Virginia Electric and Power Company. "Surry Independent Spent Fuel Storage Installation License Renewal Application." Docket No. 72–2. Richmond, Virginia: Virginia Electric and Power Company. April 29, 2002.

Table 6-6 Example aging management program for Bolted Cask Seal Leakage Monitoring

Element	Description
	_____. "Surry Independent Spent Fuel Storage Installation Completion of License Renewal Inspection Requirement." Docket No. 72–2, License Number SNM-2501. Richmond, Virginia: Virginia Electric and Power Company. August 22, 2006. Völzke, H. and D. Wolff. "Spent Fuel Storage in Dual Purpose Casks Beyond the Original Design Basis." Proceedings of the International High-Level Radioactive Waste Management Conference (IHLRWMC) April 28–May 2, 2013. La Grange Park, IL: American Nuclear Society. 2013. Völzke, H., U. Probst, D. Wolff, S. Nagelschmidt, and S. Schultz. "Seal and Closure Performance in Long Term Storage." Proceedings of the PSAM11 & ESREL 2012 Conference, Helsinki, Finland. 2012. Wolff, D., M. Jaunich, and W. Stark. "Investigating the Performance of Rubber Seals at Low Temperatures." Proceedings of the International High-Level Radioactive Waste Management Conference (IHLRWMC) April 28–May 2, 2013. La Grange Park, IL: American Nuclear Society. 2013.

6.10 Transfer Casks

An example AMP for transfer casks is provided below. The AMP manages all transfer cask subcomponents. This is a condition monitoring program that performs periodic visual inspections of accessible cask internal and external surfaces to monitor for corrosion, wear, and loss of preload (bolting). Steel neutron shield water jackets are monitored for wall thickness or inspected for through-wall leakage.

Table 6-7 Example aging management program for Transfer Casks	
Element	**Description**
1. Scope of Program	This program manages loss of material due to corrosion and wear to ensure that this aging effect does not challenge the capability of the transfer casks to fulfill structural support, radiation shielding, and heat transfer functions. Visual inspections are performed on the accessible internal and external surfaces of steel transfer cask subcomponents that are exposed to indoor and outdoor air environments. Inaccessible steel surfaces in contact with water neutron shielding are evaluated with volumetric wall thickness measurements or inspections for through-wall leakage. If not addressed with a fatigue analysis, this AMP also includes inspections of trunnions for cracking. An additional site-specific AMP may be required to manage protective coatings that are credited in the design basis for preventing corrosion of the base metal.
2. Preventive Actions	This program is a condition-monitoring program to detect evidence of degradation. It does not provide guidance for prevention of aging.
3. Parameters Monitored/ Inspected	This program monitors the condition of internal and external steel surfaces to identify general, pitting, crevice, and galvanic corrosion, and wear. The condition of inaccessible steel internal surfaces that are continuously or intermittently exposed to a liquid neutron shield are monitored from the external side of the shield shell. Parameters monitored or inspected for accessible surfaces include: • visual evidence of surface discontinuities and imperfections indicative of corrosion • visual evidence of coating degradation (e.g., blisters, cracking, flaking, delamination) indicative of corrosion of the base metal Parameters monitored or inspected to evaluate inaccessible steel surfaces exposed to a liquid neutron shield include either: • wall thickness • visual evidence of leakage on external surfaces If trunnions are not addressed with a fatigue analysis, trunnion surfaces are monitored for the presence of cracks.
4. Detection of Aging Effects	<u>Normally Accessible Surfaces</u> Visual inspections are performed in accordance with the ASME Code Section XI, Article IWA-2213, for VT-3 examinations. The inspections cover 100 percent of the normally accessible steel cask

Table 6-7 Example aging management program for Transfer Casks

Element	Description
	surfaces, including the cask exterior, cask interior cavity, lid surfaces, and the cask bottom (during lifting or down ending). Normally Inaccessible Internal Surfaces (liquid neutron shield) Wall thicknesses of steel liquid neutron shield subcomponents are measured with ultrasonic thickness techniques. Alternatively, the condition of internal surfaces of the neutron shield shell is monitored by inspections for leakage when the shield is filled with water, following ASME Code Section XI, Article IWA-2212, VT-2 (visual) inspection requirements. Trunnions If the fatigue of trunnions is not addressed with an analysis, surface or volumetric inspection techniques are performed on 100 percent of trunnion surfaces to identify the presence of fatigue cracks. Sample Size All transfer casks are inspected. Frequency Inspections are conducted at least once every 5 years. If a transfer cask is used less frequently than once every 5 years, inspections are conducted before its use in each loading campaign. Data Collection Data from the examination, including evidence of degradation and its extent and location, shall be documented on a checklist or inspection form. The results of the inspection shall be documented, including descriptions of observed aging effects and supporting sketches, photographs, or video. Corrective actions resulting from each AMP inspection shall also be documented. Timing Initial inspections are completed before the use of the transfer casks in the first loading campaign in the period of extended operation.
5. Monitoring and Trending	Inspection results are compared to those obtained during previous inspections, so that the progression of degradation can be evaluated and predicted. Monitoring and trending methods reference plans/procedures used to: • establish a baseline before or at the beginning of the period of extended operation • track trending of parameters or effects not corrected following a previous inspection

Table 6-7 Example aging management program for Transfer Casks	
Element	**Description**
	— the locations, size, and depth of any areas of corrosion — the disposition of components with identified aging effects and the results of supplemental inspections
6. Acceptance Criteria	For accessible surfaces, including trunnions, acceptance criteria are: • no detectable loss of material from the base metal, including uniform wall thinning, localized corrosion pits, crevice corrosion, and wear scratches/gouges • no red-orange-colored corrosion products on the base metal or coatings • no coating defects (e.g., blisters, cracking, flaking, delamination) For inaccessible internal surfaces, the acceptance criteria are no evidence of leakage of the water neutron shield or loss of wall thickness beyond a predetermined limit established by system-specific design standards or industry codes and standards. If evidence of corrosion, wear, or coating degradation are identified, then the severity of the degradation of the base metal must be determined using approved site-specific procedures. These may include additional visual, surface, or volumetric NDE methods to determine the loss of material. Alternative acceptance criteria are developed from system-specific design standards, industry codes or standards, or engineering evaluation. Where possible, acceptance criteria are quantitative (e.g., minimum wall thickness). Where qualitative acceptance criteria are used, the criteria are sufficiently clear to reasonably ensure that a singular decision is derived based on the observed condition, avoiding the use of ambiguous phrases (e.g., significant, moderate). EPRI Technical Reports, TR-1007933, “Aging Assessment Field Guide” (EPRI, 2003), and TR-1009743, “Aging Identification and Assessment Checklist: Mechanical Components” (EPRI, 2004), provide general guidance for the evaluation of materials and the development of criteria for their acceptance when performing visual inspections.
7. Corrective Actions	Results that do not meet the acceptance criteria are addressed as conditions adverse to quality or significant conditions adverse to quality under those specific portions of the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that corrective actions are completed within the specific- or general-licensee’s CAP, and include provisions to:

Table 6-7 Example aging management program for Transfer Casks

Element	Description
	- perform functionality assessments - perform apparent cause evaluations and root cause evaluations - address the extent of condition - determine actions to prevent recurrence for significant conditions adverse to quality; ensure justifications for nonrepairs - trend conditions - identify operating experience actions, including modification to the existing AMP (e.g., increased frequency) - determine if the condition is reportable to the NRC per 10 CFR 72.75
8. Confirmation Process	The confirmation process is commensurate with the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality. The confirmation process describes or references procedures to: - determine followup actions to verify effective implementation of corrective actions - monitor for adverse trends due to recurring or repetitive findings or observations.
9. Administrative Controls	The administrative controls are addressed through those portions of the specific or general licensee's QA program that are used to meet 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B.
10. Operating Experience	External surface inspections through system inspections and walkdowns in support of the Maintenance Rule (10 CFR Part 50.65) have proven effective in maintaining the material condition of nuclear power plant systems.
References	EPRI. "Aging Assessment Field Guide." Technical Report 1007933. Palo Alto, California: Electric Power Research Institute. December 2003. _____. "Aging Identification and Assessment Checklist–Mechanical Components." Technical Report 1009743. Palo Alto, California: Electric Power Research Institute. August 27, 2004.

6.11 High-Burnup Fuel Monitoring And Assessment

An example of a High Burnup (HBU) Fuel[1] Monitoring and Assessment Program is provided below. This is a licensee program that monitors and assesses data and other information regarding HBU fuel performance, to confirm that the design-bases HBU fuel configuration is maintained during the period of extended operation. This example HBU Fuel Monitoring and Assessment Program relies on a surrogate demonstration program to provide data on HBU fuel performance. Guidance for determining if a surrogate demonstration program can provide the data to support a licensee's HBU Fuel Monitoring and Assessment Program is given in Appendix D of NUREG–1927, Revision 1 (NRC, 2016). Although this example focuses on the use of a surrogate demonstration program, a licensee may use alternative approaches that are appropriately justified, including the use of test or research results and safety analyses for the fuel, to demonstrate that the DSS's intended functions continue to be met during the period of extended operation.

The aging management review is not expected to identify any aging effects that could lead to fuel reconfiguration, as long as the HBU fuel is stored in a dry inert environment, temperature limits are maintained, and thermal cycling is limited. Short-term testing (i.e., laboratory scale testing up to a few months) and scientific analyses examining the performance of HBU fuel have provided a foundation for the technical basis that storage of HBU fuel in the period of extended operation may be performed safely and in compliance with regulations. However, there has been relatively little operating experience, to date, with dry storage of HBU fuel.

Therefore, the purpose of a HBU Fuel Monitoring and Assessment Program is to monitor and assess data and other information regarding HBU fuel performance to confirm there is no degradation of HBU fuel that would result in an unanalyzed configuration during the period of extended operation. The following description of an example HBU Fuel Monitoring and Assessment Program presents the applicable information in a format using each element of an effective AMP, to provide a framework for such a monitoring and assessment program.

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[1] These are fuel assemblies with discharge burnup greater than 45 gigawatt-days per metric ton of uranium (GWd/MTU).

Table 6-8 Example aging management program for High-Burnup Fuel Monitoring and Assessment	
Element	**Description**
1. Scope of the Program	The scope of the program provides a description of (i) the design bases characteristics of the HBU fuel, (ii) the surrogate demonstration program that will be used to provide data on the applicable design-bases HBU fuel performance, and (iii) how the parameters of the surrogate demonstration program are applicable to the design-bases HBU fuel. Aging effects will be determined for material/environment combinations per an alternative surrogate demonstration program meeting the guidance in Appendix D of NUREG–1927, Revision 1 (NRC, 2016). Example language to address this "scope of the program" element follows: Fuel stored in a [define cask/canister model] is limited to an assembly average burnup of [define design-bases limit] GWd/MTU. The cladding materials for the HBU fuel are [define types of cladding], and the fuel is stored in a dry helium environment. HBU fuel was first placed into dry storage in a [define cask/canister model] on [start date of storage term of first storage of HBU fuel]. The program relies on the joint EPRI and DOE HBU Dry Storage Cask Research and Development Project (HDRP) (EPRI, 2014), conducted in accordance with the guidance in Appendix D of NUREG–1927, Revision 1, as a surrogate demonstration program that monitors the performance of HBU fuel in dry storage. The HDRP is a program designed to collect data from an SNF storage system containing HBU fuel in a dry helium environment. The program entails loading and storing an AREVA TN-32 bolted lid cask (the "Research Project Cask") at Dominion Virginia Power's North Anna Power Station with intact HBU fuel (of nominal burnups ranging between 53 GWd/MTU and 58 GWd/MTU). The fuel to be used in the program includes four kinds of cladding (Zircaloy-4, low-tin Zircaloy-4, ZIRLO^{TM}, and M5^{TM}). The Research Project Cask is to be licensed to the temperature limits contained in ISG-11, Rev. 3 (NRC, 2003), and loaded such that the fuel cladding temperature is as close to the limit as practicable. [If an alternative surrogate demonstration program is used, provide a description of the program.] The parameters of the surrogate demonstration program are applicable to the design-bases HBU fuel, as the (i) maximum burnup of the design-bases HBU fuel [define value] is less than the burnup of the fuel in the surrogate demonstration program [define value], (ii) the cladding type of the design-bases HBU fuel [define type] is the same as the surrogate demonstration program [define type], and (iii) the temperatures in the surrogate demonstration program [define

Table 6-8 Example aging management program for High-Burnup Fuel Monitoring and Assessment

Element	Description
	values] bound the design bases temperature/heat load of the loaded systems [define values].
2. Preventive Actions	There are no specific preventive actions associated with this HBU Fuel Monitoring and Assessment Program. However, the applicant should discuss the design-bases characteristics of the licensed/certified DSS, in terms of initial cask loading operations, to show the HBU fuel is stored in a dry inert environment. Example language follows: During the initial loading operations of the cask/canister, the design and ISFSI TS require that the fuel be stored in a dry inert environment. TS [name and number] demonstrates that the cask/canister cavity is dry by maintaining a cavity absolute pressure less than or equal to [value] for a [time period] with the cask/canister isolated from the vacuum pump. TS [name and number], requires that the cask/canister then be backfilled with helium. These two TS requirements ensure that the HBU fuel is stored in an inert environment, thus preventing cladding degradation due to oxidation mechanisms. TS [name and number] also requires that the helium environment be established within [time] hours of commencing cask/canister draining. The cask/canister is loaded in accordance with the criteria of ISG-11, Revision 3 (NRC, 2003).
3. Parameters Monitored or Inspected	The applicant identifies the parameters monitored and inspected in a surrogate demonstration program that are applicable to its particular design-bases HBU fuel and describes how this meets the guidance of Appendix D of NUREG–1927, Revision 1.
4. Detection of Aging Effects	The applicant identifies the detection of aging effects in a surrogate demonstration program that are applicable to its particular design-bases HBU fuel and describes how this meets the guidance of Appendix D of NUREG–1927, Revision 1.
5. Monitoring and Trending	As information/data from a surrogate demonstration program or from other sources (such as testing or research results and scientific analyses) become available, the licensee will monitor, evaluate, and trend the information via its operating experience program and/or the CAP to determine what actions should be taken. The licensee will evaluate the information/data from a surrogate demonstration program or from other sources to determine whether the acceptance criteria in Element 6 are met. • If all of the acceptance criteria are met, no further assessment is needed. • If any of the acceptance criteria are not met, the licensee must conduct additional assessments and implement appropriate corrective actions (see Element 7).

Table 6-8 Example aging management program for High-Burnup Fuel Monitoring and Assessment	
Element	**Description**
	Formal evaluations of the aggregate information from a surrogate demonstration program and other available domestic or international operating experience (including data from monitoring and inspection programs, NRC-generated communications, and other information) will be performed at specific points in time during the period of extended operation, as delineated in Table B-4 of NUREG–1927, Revision 1.
6. Acceptance Criteria	The HBU Fuel Monitoring and Assessment Program acceptance criteria are: • hydrogen content–Maximum hydrogen content of the cover gas over the approved storage period should be extrapolated from the gas measurements to be less than the design-bases limit for hydrogen content. • moisture content–The moisture content in the cask/canister, accounting for measurement uncertainty, should be less than the expected upper-bound moisture content per the design-bases drying process[1]. • fuel condition/performance[2]–nondestructive examination (e.g., fission gas analysis) and destructive examination (e.g., to obtain data on creep, fission gas release, hydride reorientation, cladding oxidation, and cladding mechanical properties) should confirm the design-bases fuel condition (i.e., no changes to the analyzed fuel configuration considered in the safety analyses of the approved design bases). The applicant should provide information on the design-bases characteristics of the DSS, with regard to these criteria. The applicant should reference the source of specific values, or explain any assumptions made, for defining design-bases characteristics of the fuel condition/performance.
7. Corrective Actions	The corrective actions are in accordance with the specific or general licensee QA program and consistent with 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. Corrective actions should be implemented if data from a surrogate demonstration program or other sources of information indicate that

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[1] The applicant will need to provide the expected upper-bound moisture content based on its design-bases drying process. If the design-bases drying process involves a vacuum drying method of evacuating a cask/canister to less than or equal to 3 torr and maintaining a constant pressure for 30 minutes after the cask/canister is isolated from the vacuum pump, the expected water content is about 0.43 gram-mole. (See NRC, 2010.)

[2] While it is not a fuel performance criterion, the spatial distribution and time history of the temperature must be known to evaluate the relationship between the performance of the rods in a surrogate demonstration program and the HBU fuel rod behavior expected in the cask.

Table 6-8 Example aging management program for High-Burnup Fuel Monitoring and Assessment	
Element	**Description**
	any of the HBU Fuel Monitoring and Assessment Program acceptance criteria (in Element 6) are not met. If any of the acceptance criteria are not met, the licensee will: (i) assess fuel performance (impacts on fuel and changes to fuel configuration) (ii) assess the design-bases safety analyses, considering degraded fuel performance (and any changes to fuel configuration), to determine the ability of the DSS to continue to perform its intended functions under normal, off-normal, and accident conditions. The licensee will determine what corrective actions should be taken to: (i) manage fuel performance, if any (ii) manage impacts related to degraded fuel performance to ensure that all intended functions for the DSS are met. In addition, the licensee will obtain the necessary NRC approval in the appropriate licensing/certification process for modification of the design bases to address any conditions outside of the approved design bases.
8. Confirmation Process	The confirmation process is commensurate with the specific- or general-licensee QA program approved under 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality. The confirmation process describes or references procedures to: • determine followup actions to verify effective implementation of corrective actions • monitor for adverse trends due to recurring or repetitive findings or observations.
9. Administrative Controls	The administrative controls are in accordance with the specific or general licensee QA program and consistent with 10 CFR Part 72, Subpart G, or 10 CFR Part 50, Appendix B, respectively. The QA program ensures that the administrative controls include provisions that define: • formal review and approval processes • record retention requirements • document control

Table 6-8 Example aging management program for High-Burnup Fuel Monitoring and Assessment	
Element	**Description**
10. Operating Experience	The program references and evaluates applicable operating experience, including: • internal and industrywide condition reports • internal and industrywide corrective action reports • vendor-issued safety bulletins • NRC Information Notices • applicable DOE or industry initiatives (e.g., HDRP) • applicable research (e.g., Oak Ridge National Laboratory studies on bending responses of the fuel, Argonne National Laboratory and Central Research Institute of Electric Power Industry studies on hydride reorientation effects) The review of operating experience clearly identifies any HBU fuel degradation as either age related or event driven, with proper justification for that assessment. Past operating experience supports the adequacy of the HBU Fuel Monitoring and Assessment Program. Surrogate demonstration programs with storage conditions and fuel types similar to those in the licensed/certified DSS that meet the guidance in Appendix D of NUREG–1927, Revision 1, are a viable method to obtain operating experience. New data/research on fuel performance from both domestic and international sources that are relevant to the licensed/certified HBU fuel in the DSS should be evaluated on a periodic basis.
References	EPRI. “HBU Dry Storage Cask Research and Development Project Final Test Plan.” DOE Contract No.: DE-NE-0000593. Palo Alto, California: Electric Power Research Institute. 2014. NRC. “NRC Interim Staff Guidance 11, “Cladding Considerations for the Transportation and Storage of Spent Fuel.” Rev. 3. ADAMS Accession No. ML033230335. Washington, DC: U.S. Nuclear Regulatory Commission. November 17, 2003. _____. NUREG–1536, “Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility.” Rev. 1. ADAMS Accession No. ML101040620. Washington, DC. U.S. Nuclear Regulatory Commission. 2010. _____. NUREG–1927, “Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel.” Revision 1. ADAMS Accession No. ML16179A148. Washington, DC: U.S. Nuclear Regulatory Commission. 2016. .

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11. ABSTRACT (200 words or less)
This Managing Aging Processes in Storage (MAPS) Report provides guidance for the U.S. Nuclear Regulatory Commission (NRC) technical reviewer. It establishes a technical basis for the safety review of renewal applications for specific licenses of independent spent fuel storage installations and Certificates of Compliance for dry storage systems, as codified in Title 10 of the Code of Federal Regulations Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High Level Radioactive Waste, and Reactor Related Greater Than Class C Waste."

The MAPS Report evaluates known aging degradation mechanisms to determine if they could affect the ability of dry storage system components to fulfill their safety functions in the 20- to 60 year period of extended operation. The guidance also provides examples of aging management programs that are considered generically acceptable to address the credible aging mechanisms to ensure that the design bases of dry storage systems will be maintained. An applicant for a renewed license or Certificate of Compliance may reference the information in the MAPS Report to support its aging management review and proposed aging management programs.

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